ILC and LCLS-II

SRF Construction Experience relevant to HEP

Marc Ross (SLAC LCLS-II)

HEPAP Accelerator R&D Subpanel

August 29, 2014

Outline

1. Industrialization of 1.3 GHz SRF technology
   - 1990's to present
   - TESLA, E-XFEL, and ILC (also CEBAF 12 GeV)
2. LCLS-II
   - Free Electron Laser at SLAC – based on ILC / E-XFEL SRF
3. SRF for LCLS-II
   - Low cryogenic-loss cavities: 'N_2 doping' process developed by Fermilab
   - Multi-lab partnership
4. Implications for ILC

SRF: ILC ↔ LCLS-II ↔ ILC

Before: TESLA Collaboration, XFEL, SRF R&D

2013: ILC TDR International Review (Feb)

Performance Demonstrations, Industrialization, Cost

2013: LCLS-II CW SRF Linac proposed to DoE – SC(BES)

CD-0 (Aug), CD-1 (Aug 2014), CD-2/3 (3QFY15)

2014: High Q0 Process development (Apr – Sep)

Fermilab (lead), JLab, Cornell; (Cavities from FNAL)

2018: LCLS-II Cryomodule Construction Complete (Aug)

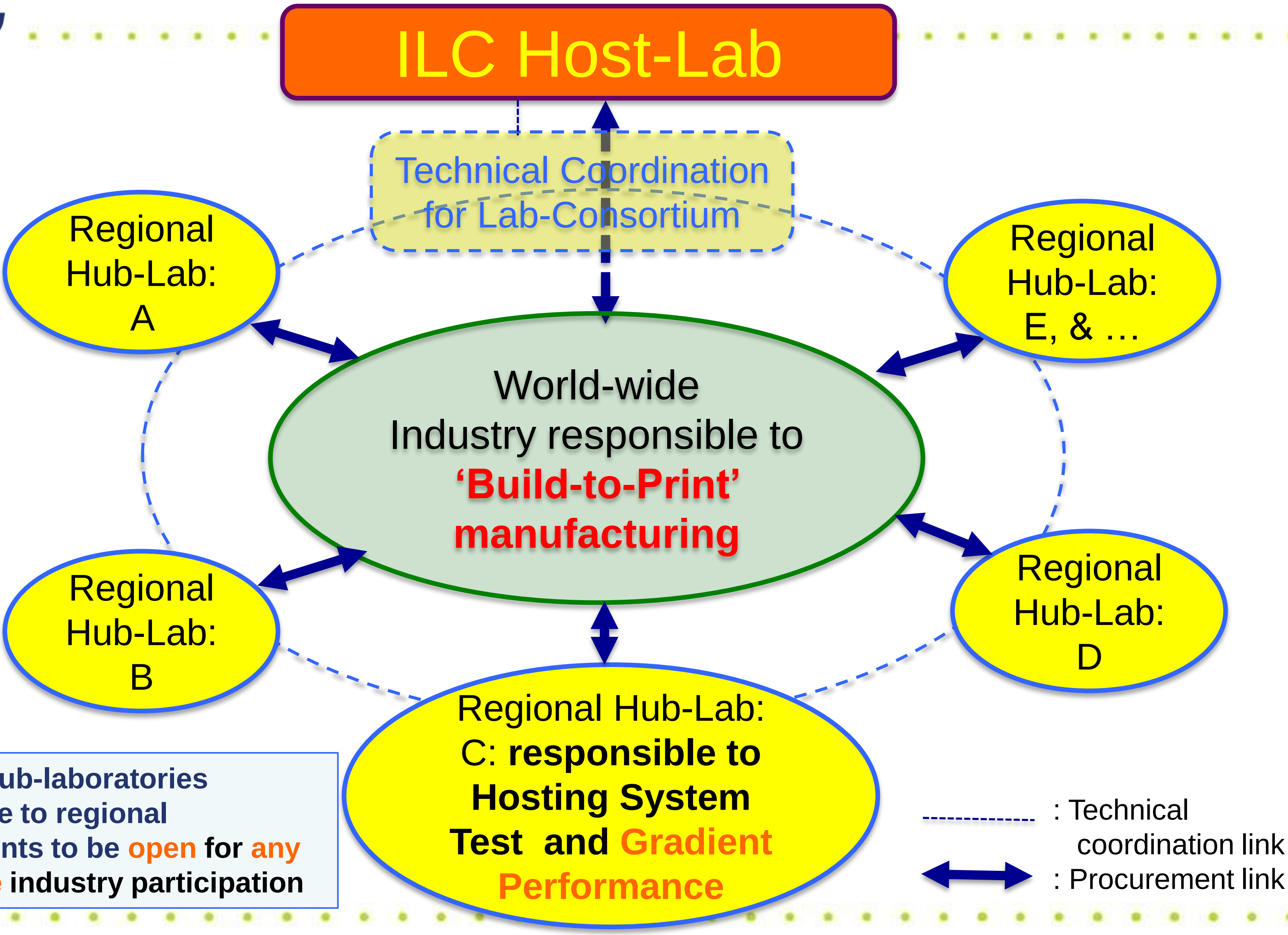
→ *First light at end of FY2019*

2018: US Infrastructure Qualified and Demonstrated

→ *ready for ILC or ?*

SRF Cost Reduction / Risk Reduction through application

SCRF Procurement/Manufacturing Model

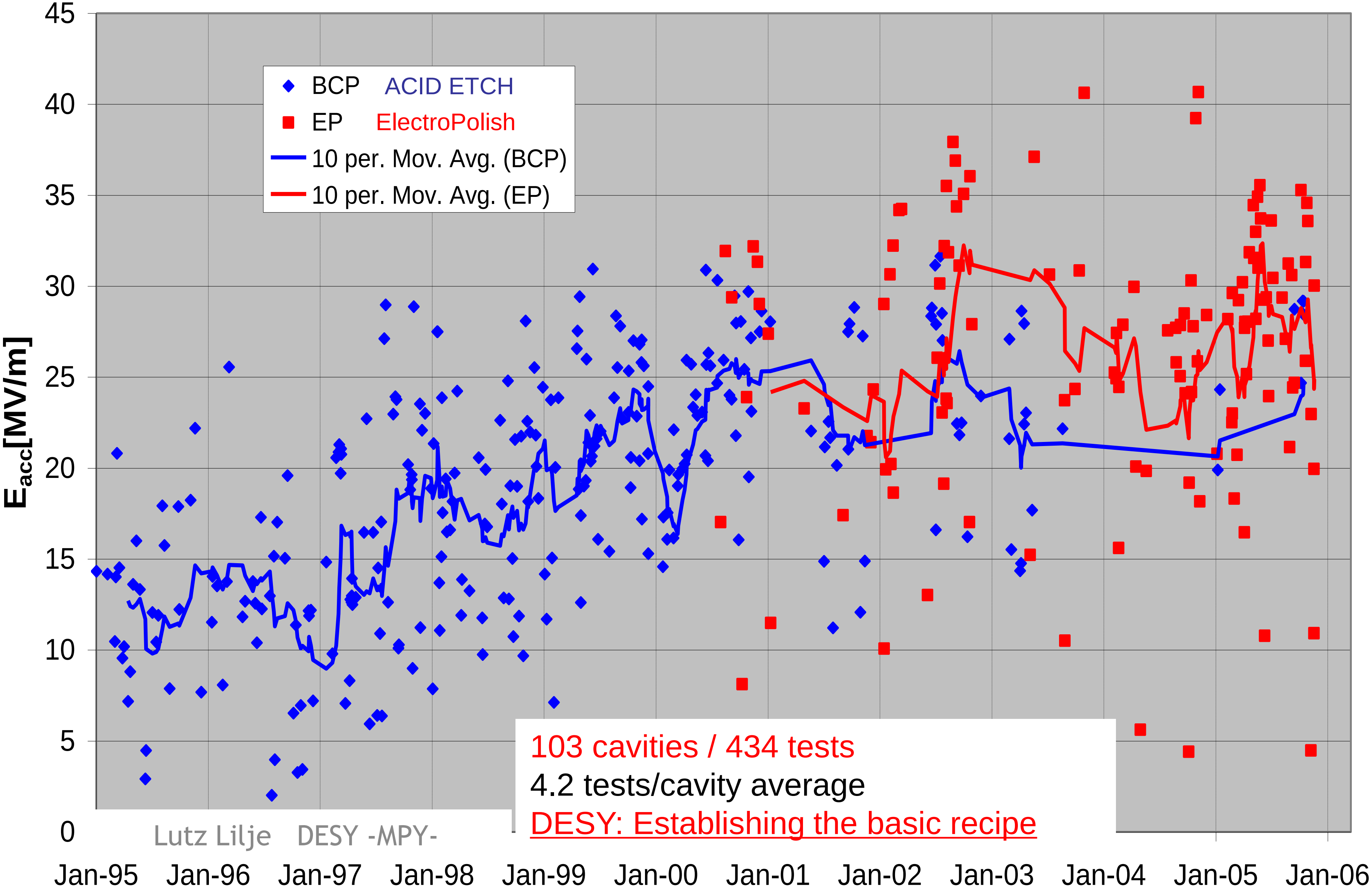


Regional hub-laboratories responsible to regional procurements to be open for any world-wide industry participation

A Model for Cavity and CM Production and Qualification Process

Step hosted	Industry	Industry/Laboratory	Hub-laboratory	ILC Host-laboratory
Regional constraint	no	yes or no	yes	yes
Sub-comp/material - Production/Procurement	Nb, Ti, specific comp. …		Procurement	
9-cell Cavity - Manufacturing	9-cell-cavity, Process, He-Jacketing		Procurement	
9-cell Cavity - Performance Test			Cold, gradient test	
Cryomodule component - Manufacturing	V. vessel, cold-mass ...		Procurement	
Cryomodule/Cavity - Assembly		Cav-string/ CM-assembly		
SCRF Cryomodule - Perofrmance Test			Cold, gradient test	
Accelerator integration, Commissioning				Accelerator sys. Integ.

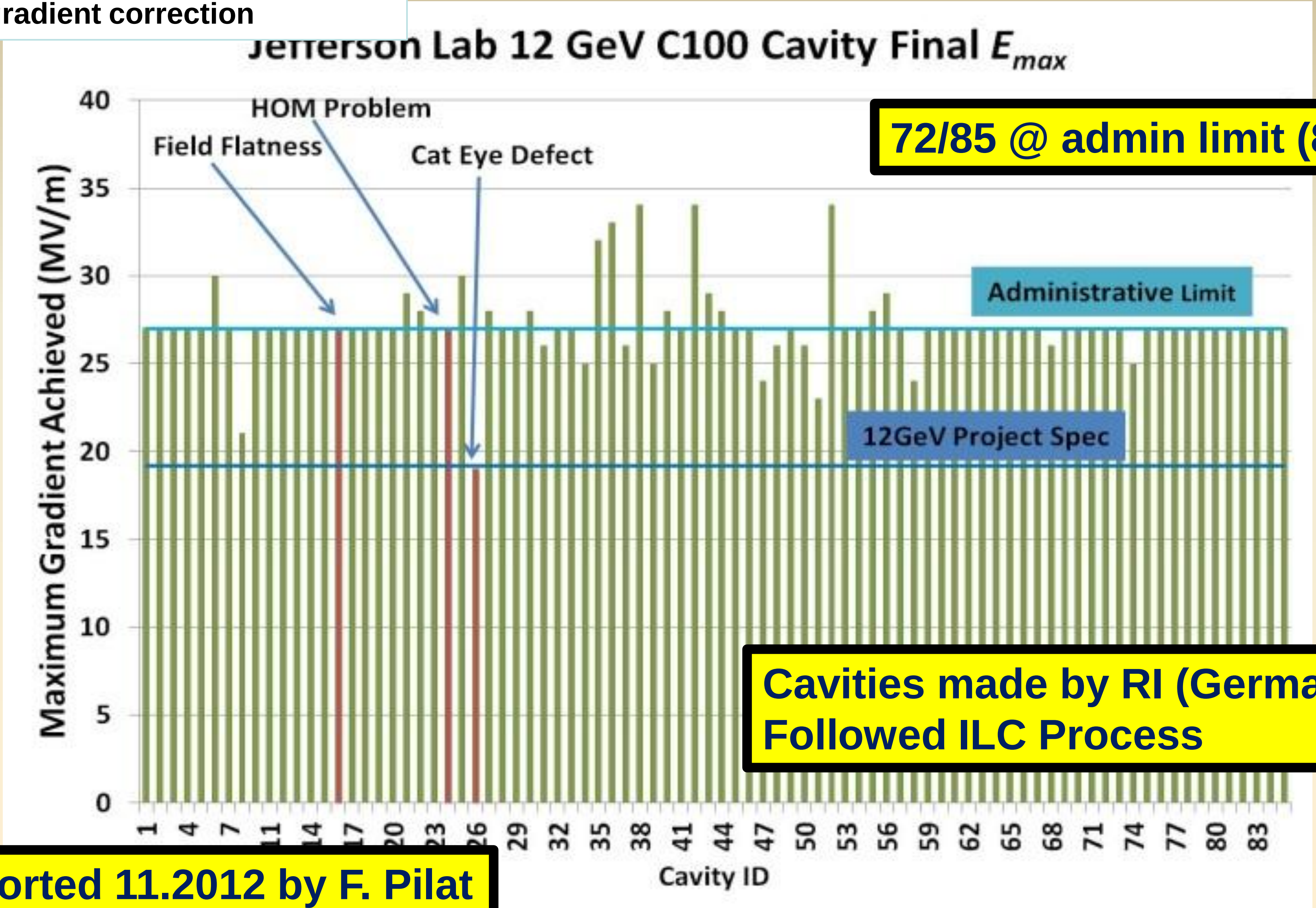
Vertical Cavity Test Results at DESY: 1995-2006



CEBAF 12 GeV upgrade

12 GeV cavities: overall performance

Vertical Test; 1500 MHz 7 cell; 10% gradient correction

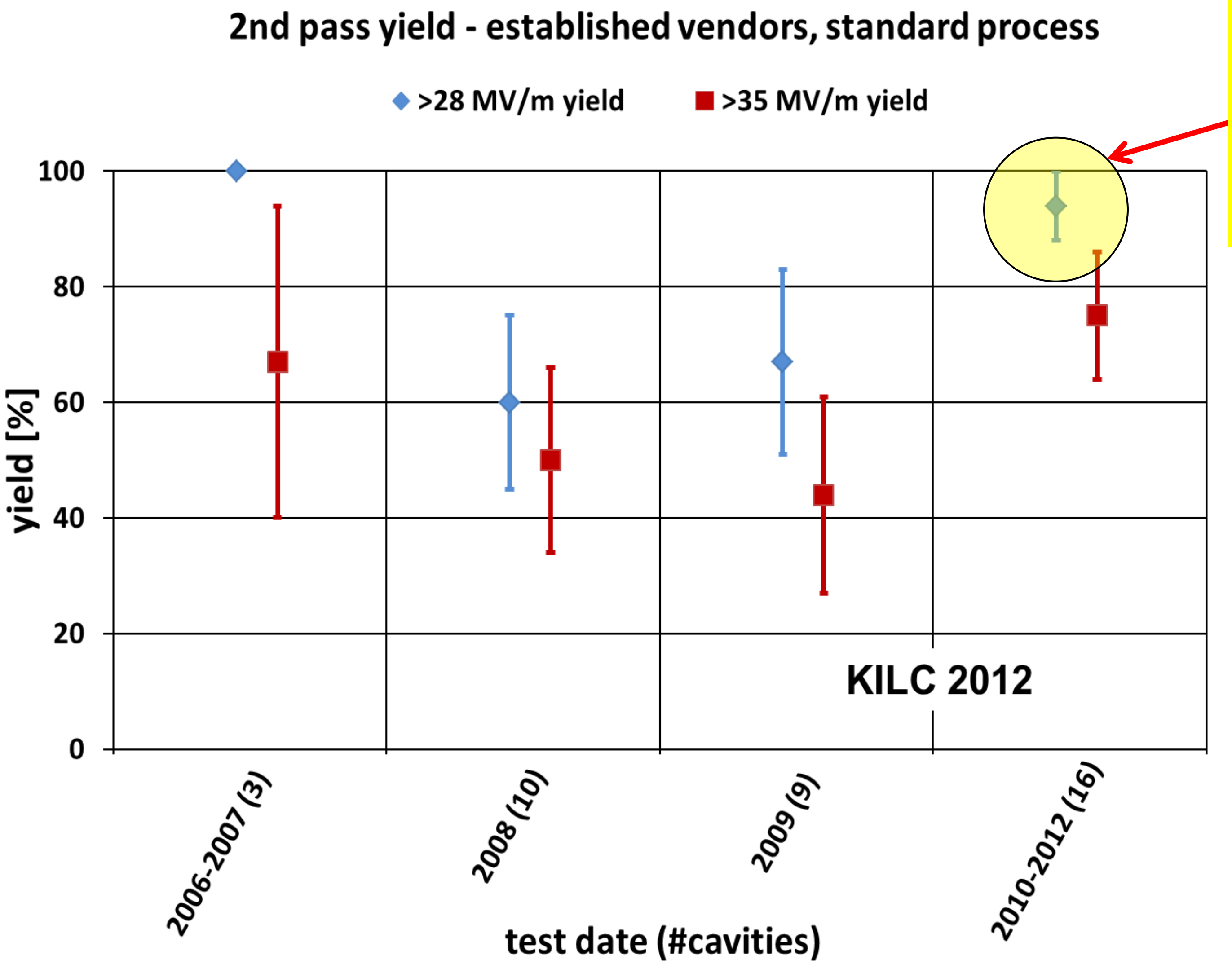


72/85 @ admin limit (85%)

Cavities made by RI (Germany); Followed ILC Process

Reported 11.2012 by F. Pilat

Global Progress in ILC Cavity Gradient Yield



(94+/-6)% acceptable for ILC mass production

E.ZANON S.p.A.

research instruments

2 Europe
3 Americas
4 Asia

Advanced Energy Systems, Inc.

NIOWAVE
www.niowaveinc.com

PAVAC INDUSTRIES INC.

MITSUBISHI HEAVY INDUSTRIES, LTD.
Our Technologies, Your Tomorrow

TOSHIBA
Leading Innovation >>>

HITACHI
Inspire the Next

Global Industrial Cavity Fabrication Partners – *qualified**

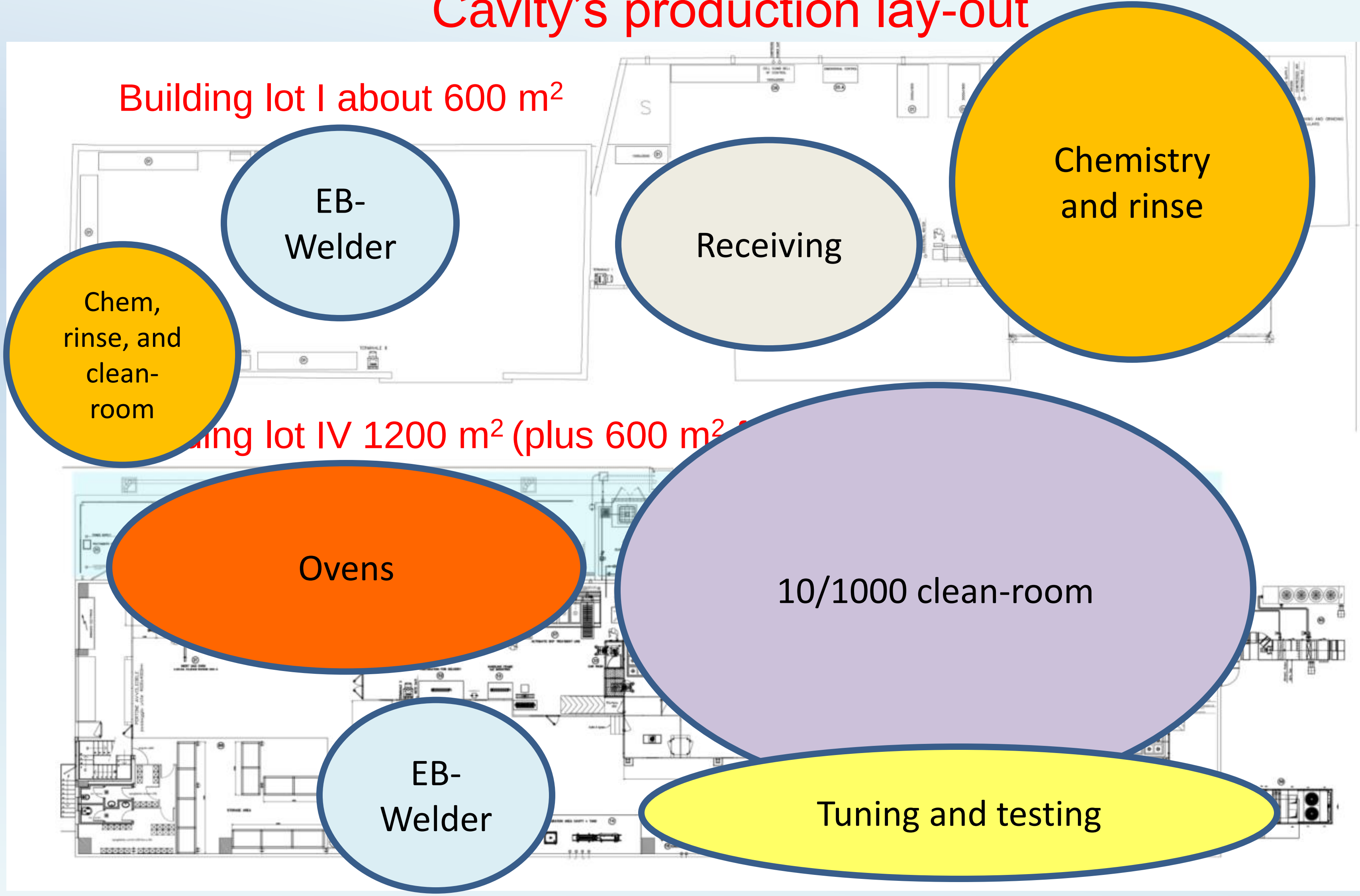
宁夏东方钽业股份有限公司
NINGXIA ORIENT TANTALUM INDUSTRY CO.,LTD.

* (or soon to be)

E.ZANON S.p.A.

Infrastructure for SC cavities production (D)

Cavity's production lay-out



An Accelerator Complex for 17.5 GeV

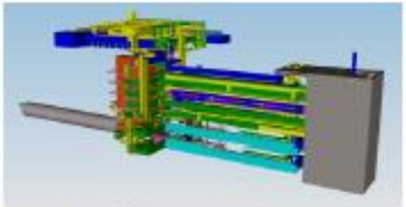
100 accelerator modules

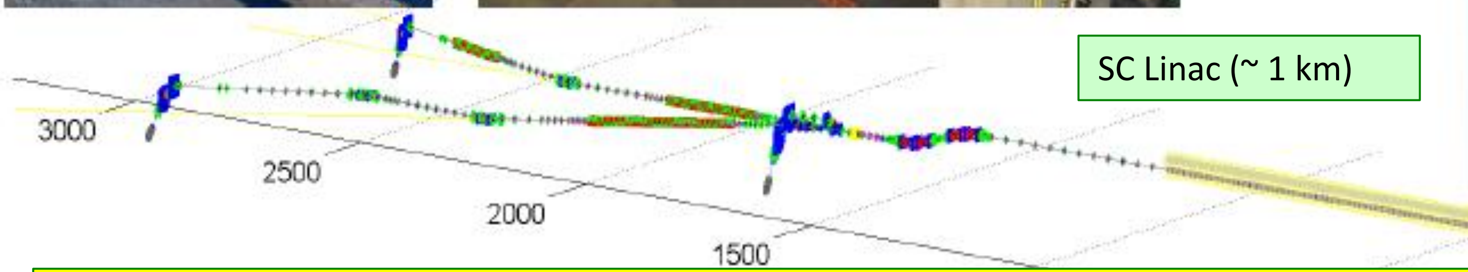
Some specifications

- Photon energy 0.3 - 24 keV
- Pulse duration ~ 10 - 100 fs
- Pulse energy few mJ
- Superconducting linac. 17.5 GeV
- 10 Hz (27 000 b/s)

800 accelerating cavities
1.3 GHz / 23.6 MV/m

25 RF stations
5.2 MW each

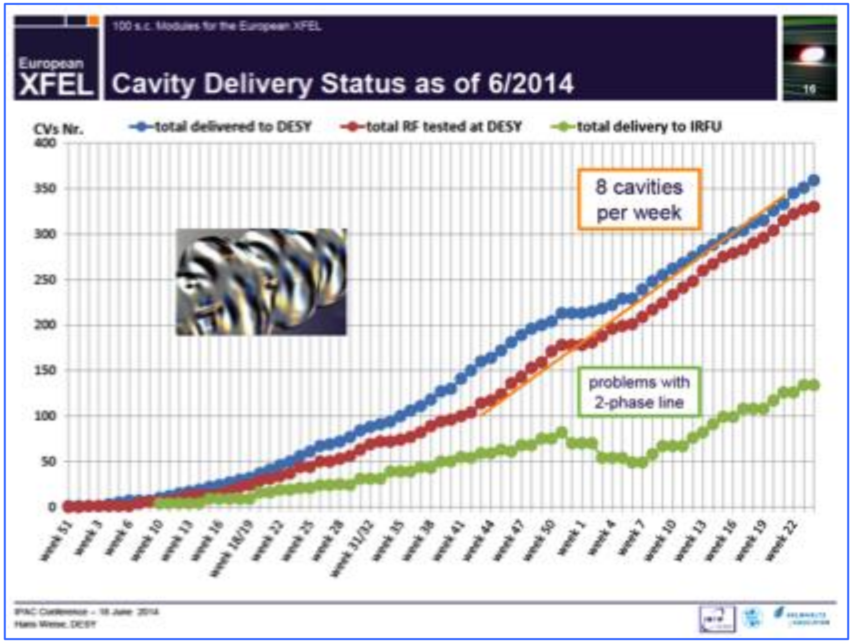




EXFEL: 1/20 Scale Project on going, Industrialization being verified !!

IPAC14: Courtesy: H. Weise

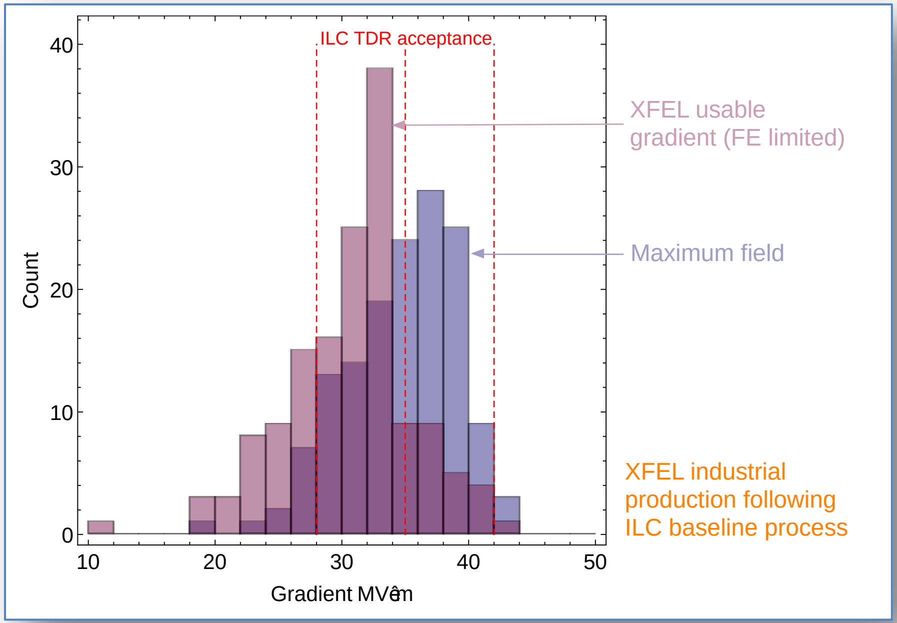
SCRF Cavity Production



- **Gradients** in average above specification (almost 300 cavities tested)
  - Average usable gradient after delivery (26.8 ± 7.1) MV/m
  - 2/3 of cavities can be used w/o further treatment
  - 1/3 is getting additional treatm. -> usable grad. increased to (29.6 ± 5.1) MV/m

2014.6: # cavities produced > 300. Usable Gradient: ~ < 30 > MV/m

SCRF Cavity Production



- **Gradients** in average above specification (almost 300 cavities tested)
  - Average usable gradient after delivery (26.8 ± 7.1) MV/m
  - 2/3 of cavities can be used w/o further treatment
  - 1/3 is getting additional treatm. -> usable grad. increased to (29.6 ± 5.1) MV/m

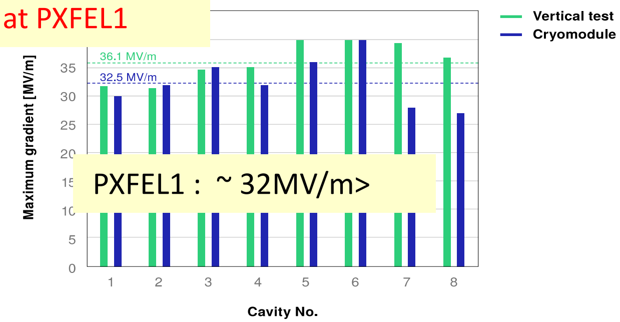
2014.6: # cavities produced > 300. Usable Gradient: ~ < 30 > MV/m

Cryomodule System Test

DESY: FLASH

- 1.25 GeV linac (TESLA-Like tech.)
- ILC-like bunch trains:
- 600 ms, 9 mA beam (2009) ← Demonstrated
  800 ms 4.5 mA (2012)
- RF-cryomodule string with beam → PXFEL1 operational at FLASH

XFEL Prototype at PXFEL1

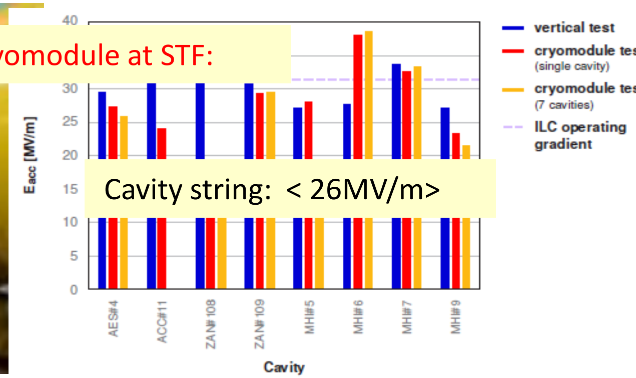


PXFEL1 : ~ 32MV/m>

KEK: STF/STF2

- S1-Global: completed (2010)
- Quantum Beam Accelerator (Inverse Llaser Compton): 6.7 mA, 1 ms ← Demonstrated
- CM1 test with beam (2014 ~2015)
- STF-COI: Facility to demonstrate CM assembly/test in near future

S1 Global Cryomodule at STF:



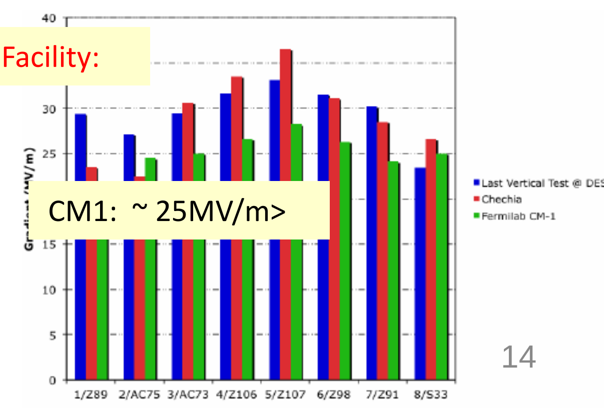
Cavity string: < 26MV/m>

FNAL: ASTA

(Advanced Superconducting Test Accelerator)

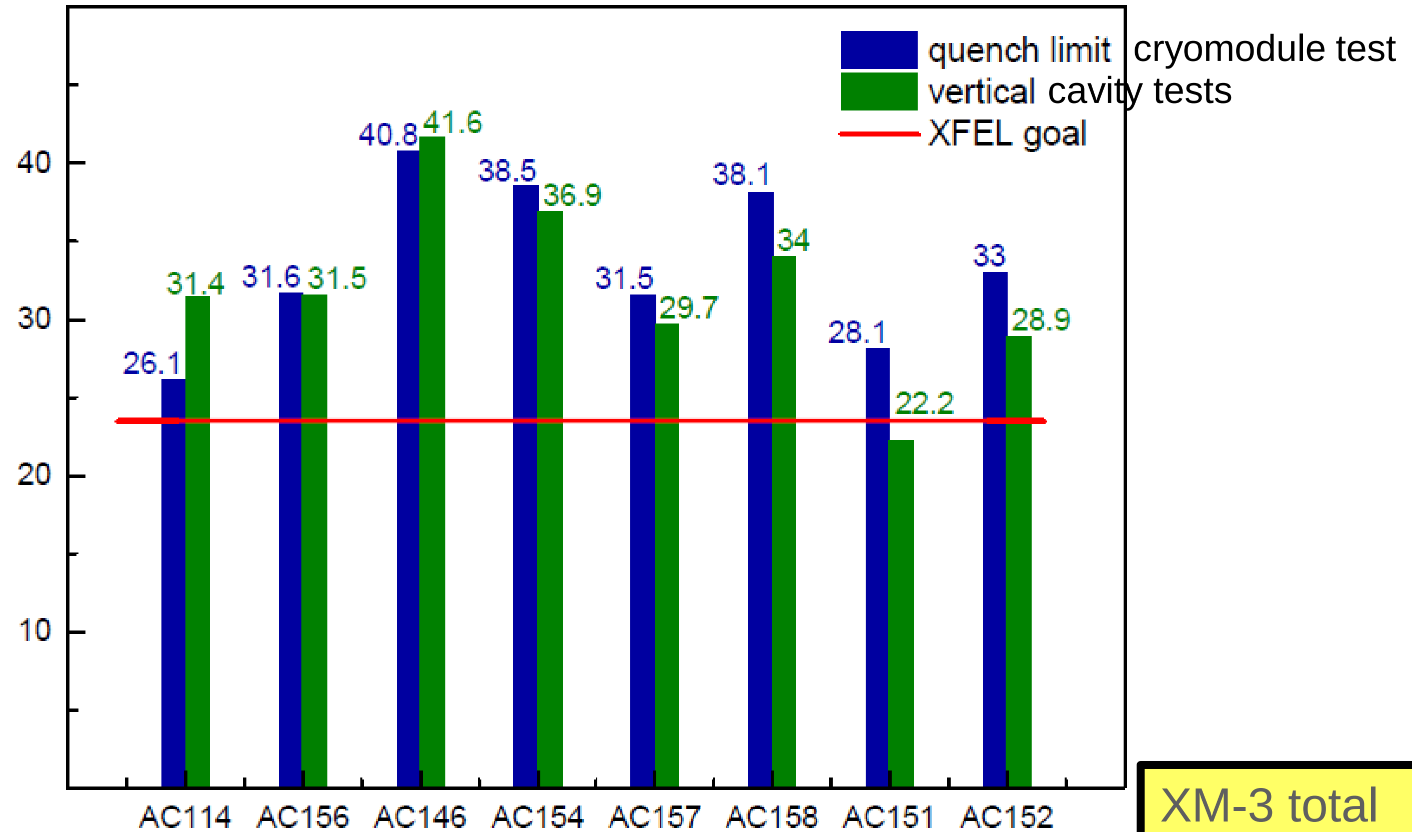
- CM1 test complete
- CM2 operation (2013)
- CM2 with beam (soon)

CM1 at NML Facility:



CM1: ~ 25MV/m>

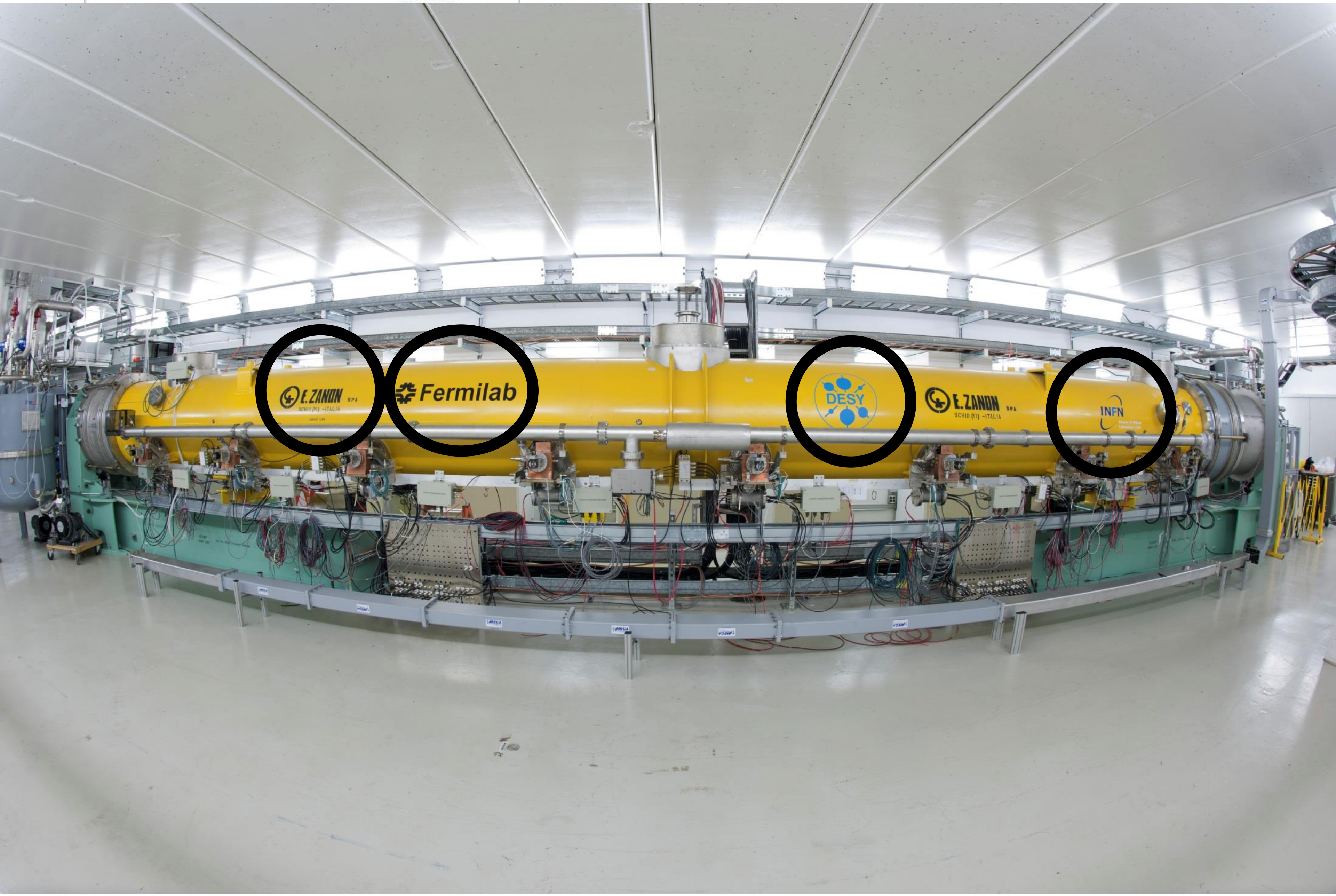
XM-3 RF Test Results



Gate valve	CV 1	CV2	CV3	CV4	CV5	CV6	CV7	CV8	BQU		
	AC114	AC156	AC146	AC154	AC157	AC158	AC151	AC152			
Eacc (VT)	31,4	31,5	41,5	36,9	29,7	38,8	22,2	28,9			
Fe limit (VT)	31,4	31,5	41	36,9	29,7	38,8	16,8	20		**229,6**	**MV**
CMTB	23,2	31,4	40,8	38,5	31,5	38,1	22,7	33		**231,8**	**MV**
										29,0	MV/m

XM-3 total gradient compared with VT

Will it work ? System Tests - Fermilab

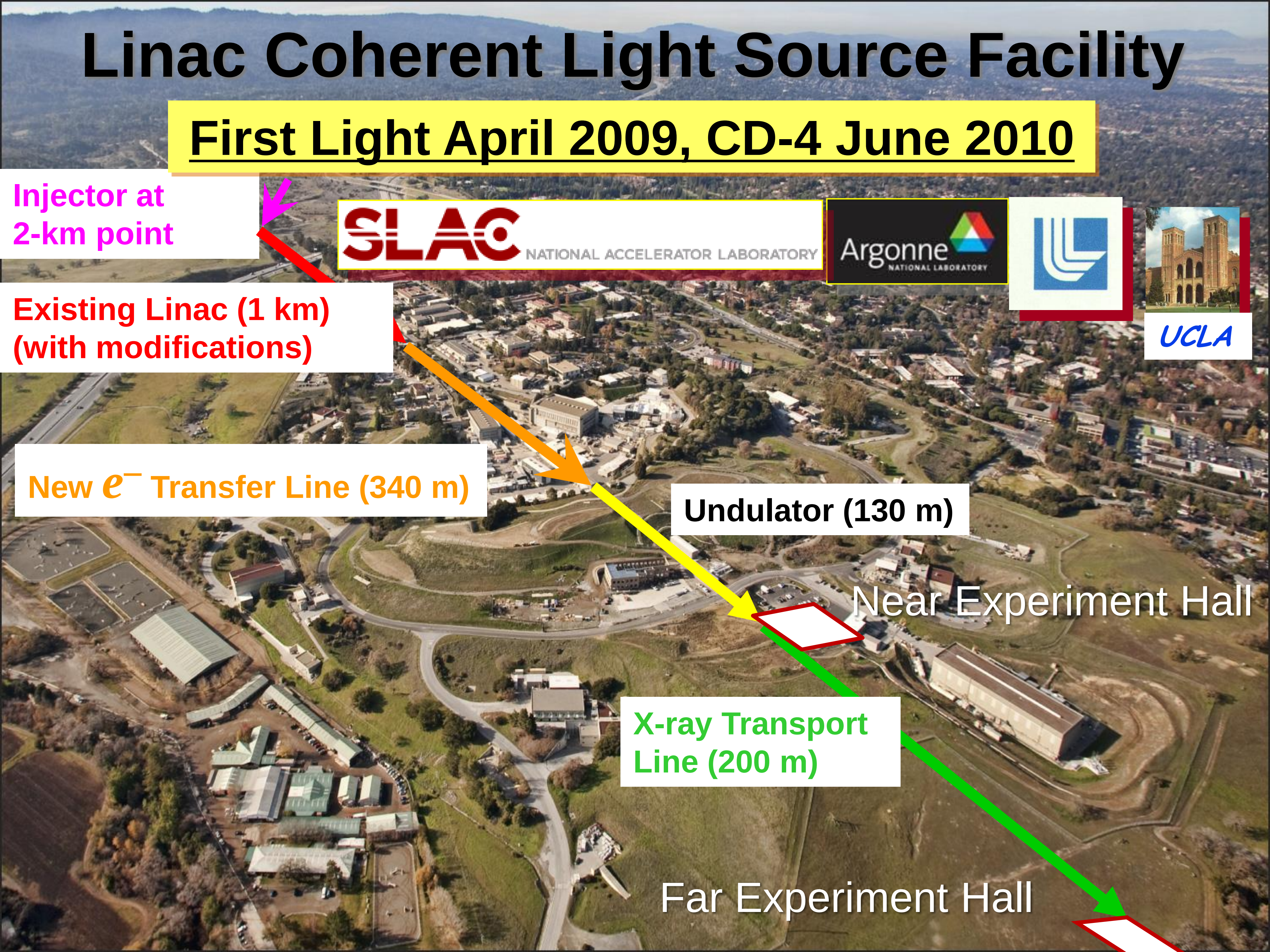


Outline

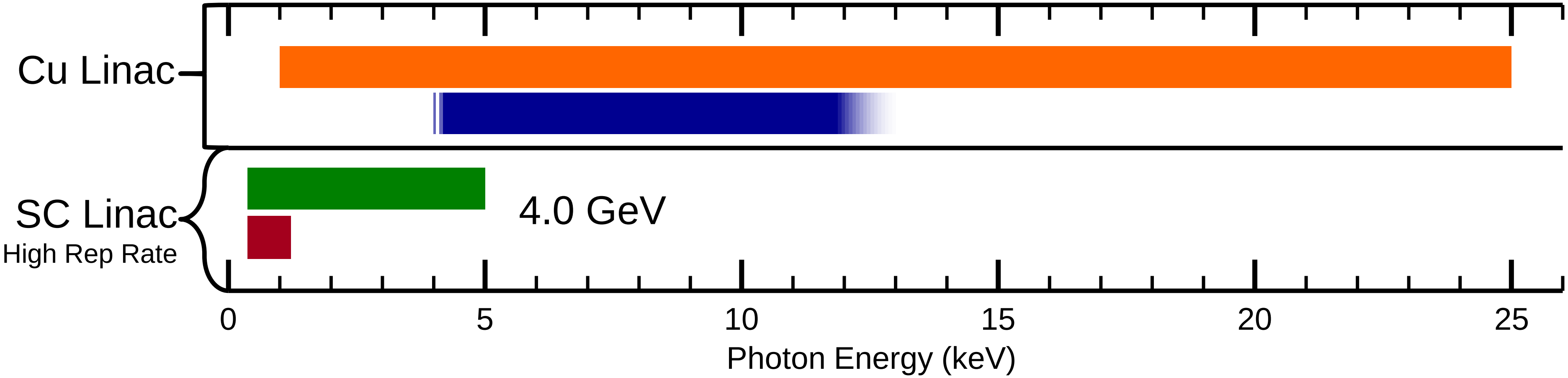
1. Industrialization of 1.3 GHz SRF technology
   - 1990's to present
   - TESLA, E-XFEL, and ILC (also CEBAF 12 GeV)
2. LCLS-II
   - Free Electron Laser at SLAC – based on ILC / E-XFEL SRF
3. SRF for LCLS-II
   - Low cryogenic-loss cavities: 'N_2 doping' process developed by Fermilab
   - Multi-lab partnership
4. Implications for ILC

Linac Coherent Light Source Facility

First Light April 2009, CD-4 June 2010



Photons for Basic Energy Science (Material, Condensed Matter, Biology, Chemistry…)

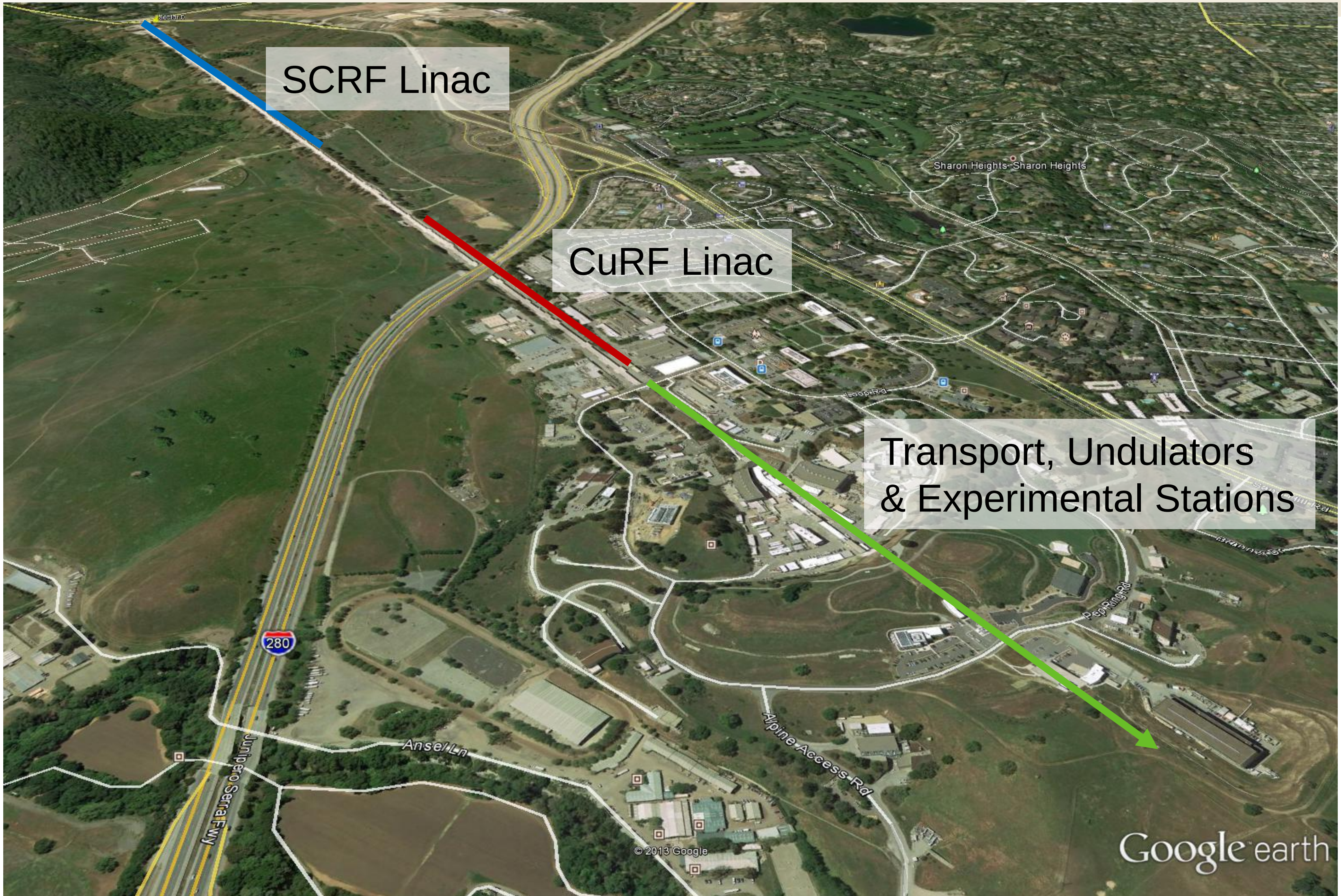


Legend

- Cu SASE
- Cu Self Seeded
- High Rep Rate SASE
- Self Seeded (Grating)

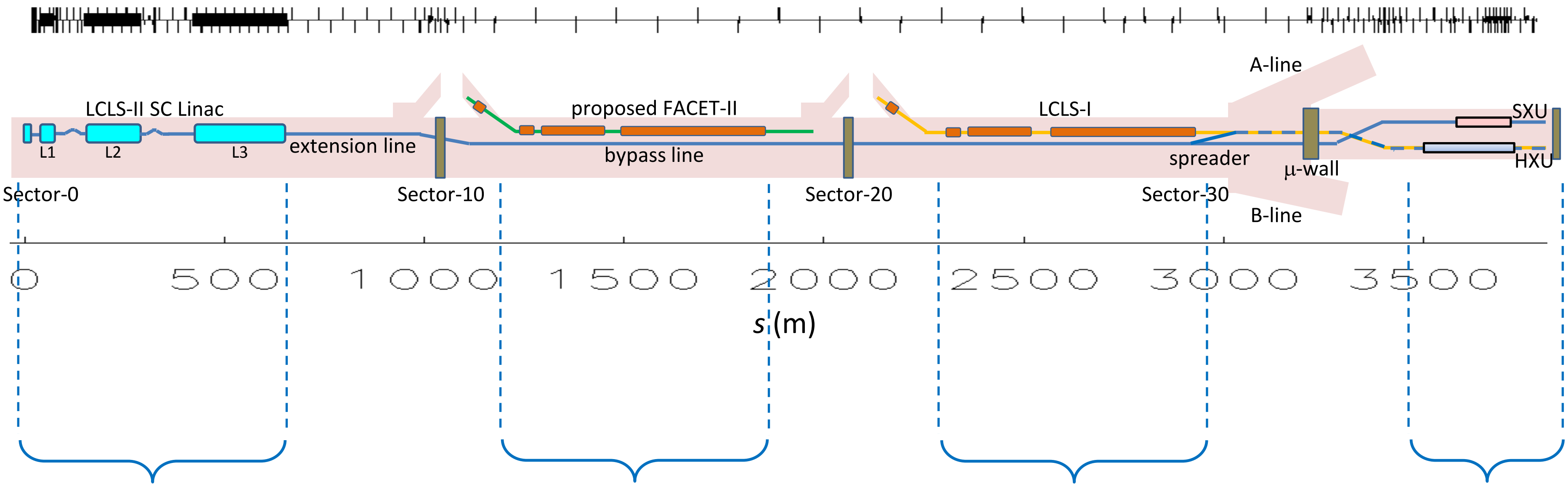
- Hard X-Ray Source:
  - 1-5 keV w/ new 4 GeV SC linac
  - Up to 25 keV with LCLS Cu Linac
- Soft X-Ray Source:
  - 250 eV-1.2 keV w/ 4 GeV linac
- ***Both linacs feed HXR undulator***

LCLS-II Concept
Use 1st km of SLAC linac for CW SCRF linac



LCLS-II Layout in SLAC Linac Tunnel

(only approximately to scale)



New SCRF Linac (4 GeV)

Proposed FACET-II and Bypass Line

Existing LCLS-I Linac

Undulators (LCLS-I & -II)

LCLS-II Objectives:

- Build 4 GeV (up to 300 micro-Amp) CW superconducting linac based on TESLA / ILC / E-XFEL 1.3 GHz technology
- Develop cavity process for high-Q0 production
- Develop CW cryomodule design and operations scheme for 110 W @ 2K / CM (or better) based on high-Q0 cavity process
- Use industrial capability for 1) dressed-processed-cavity, 2) coupler, and 3) vacuum-vessel/cold-mass production
- Adapt JLab ‘CHL-2’ (12 GeV Upgrade) Cryoplant for SLAC

LCLS-II Cavity Control

10 to 100x lower current than ILC / XFEL

- (LCLS-II 60 micro Amp / EXFEL - ILC 6 mA)
- → Matched LCLS-II loaded Q_L ~ 3e8; effective resonance width very narrow; BW few Hz
- Difficult with today's state-of-the-art cavity controls

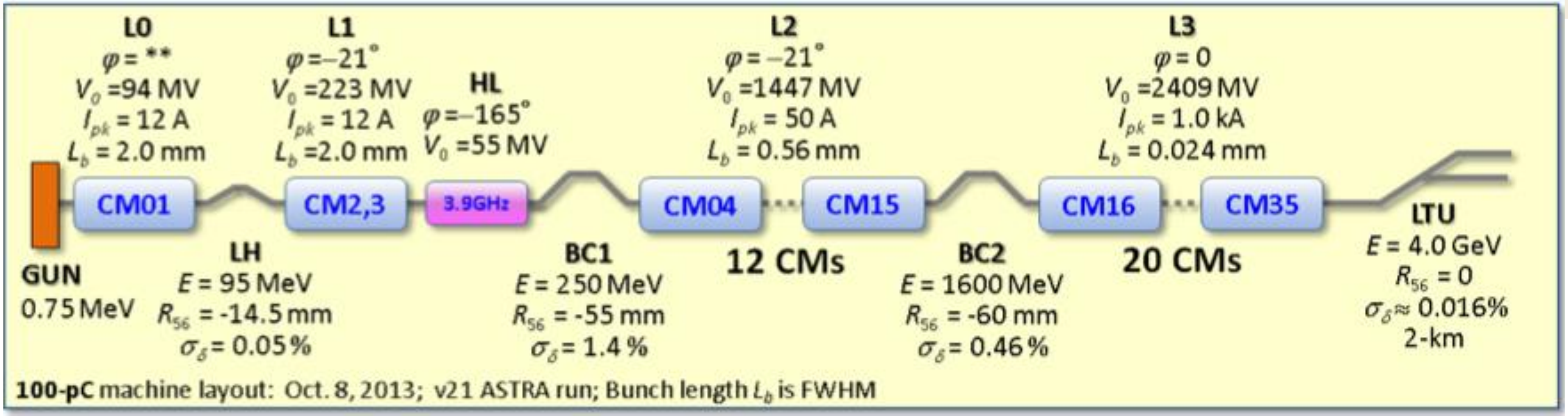
LCLS-II: $6e6 < Q_L < 1e8$; nominal 4e7 BW 50 Hz

ILC / XFEL: $1e6 < Q_L < 1.4e7$

Microphonics / cavity resonance control → key R&D topics for low current CW linacs

- Also useful for ILC

LCLS-II Linac



Closely based on the ***European XFEL / ILC / TESLA*** Design

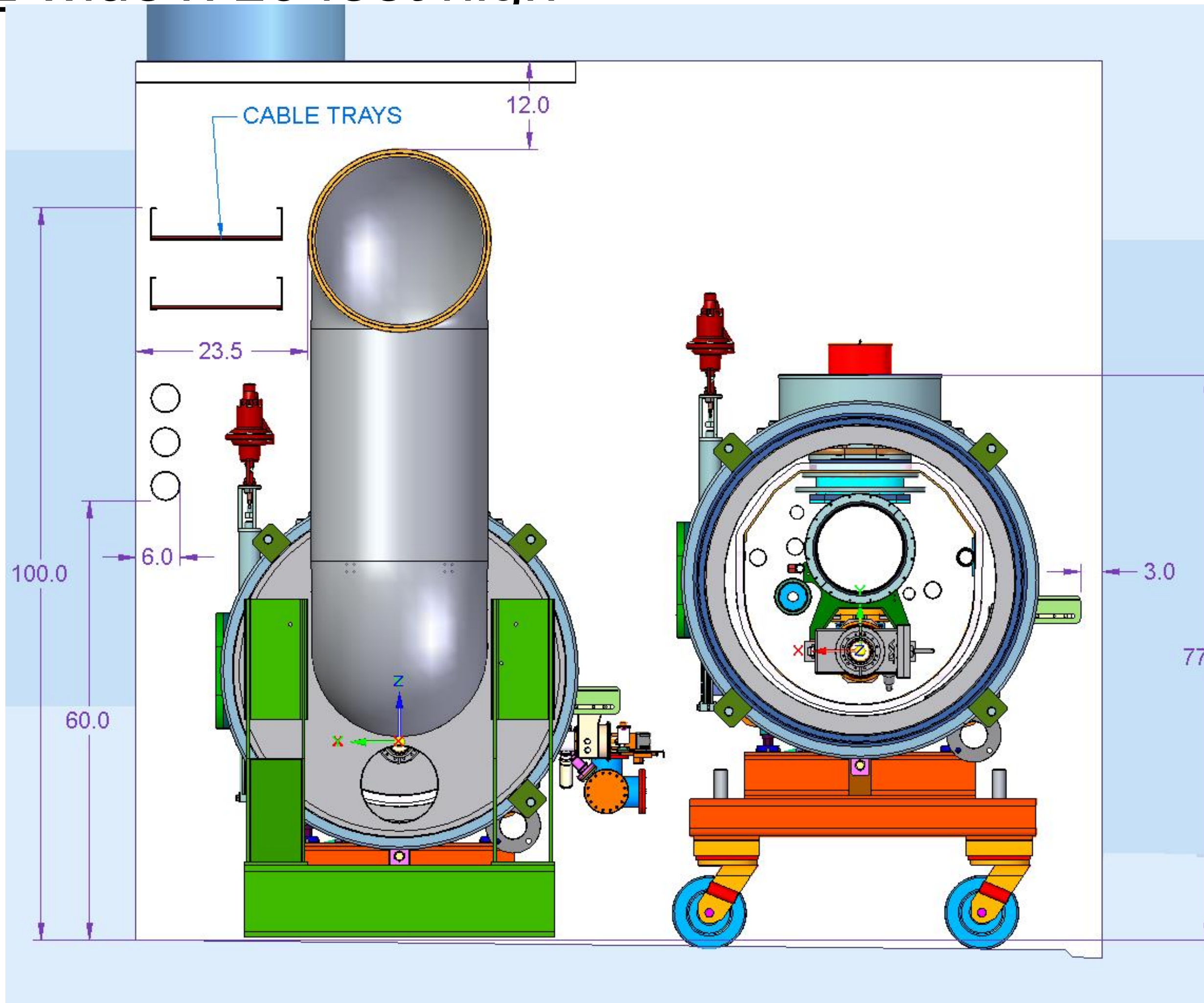
Under development ~ 20 years with ***> 1000 cavities*** to be made and tested (inc. 800 for E-XFEL – completed 2016)

- Thirty-five **1.3 GHz 8-cavity cryomodules**
- Two **3.9 GHz 8-cavity cryomodules**
- Four cold segments (L0, L1, L2 and L3) which are separated by warm beamline sections.
- 280 1.3 GHz cavities
- 16 3.9 GHz cavities

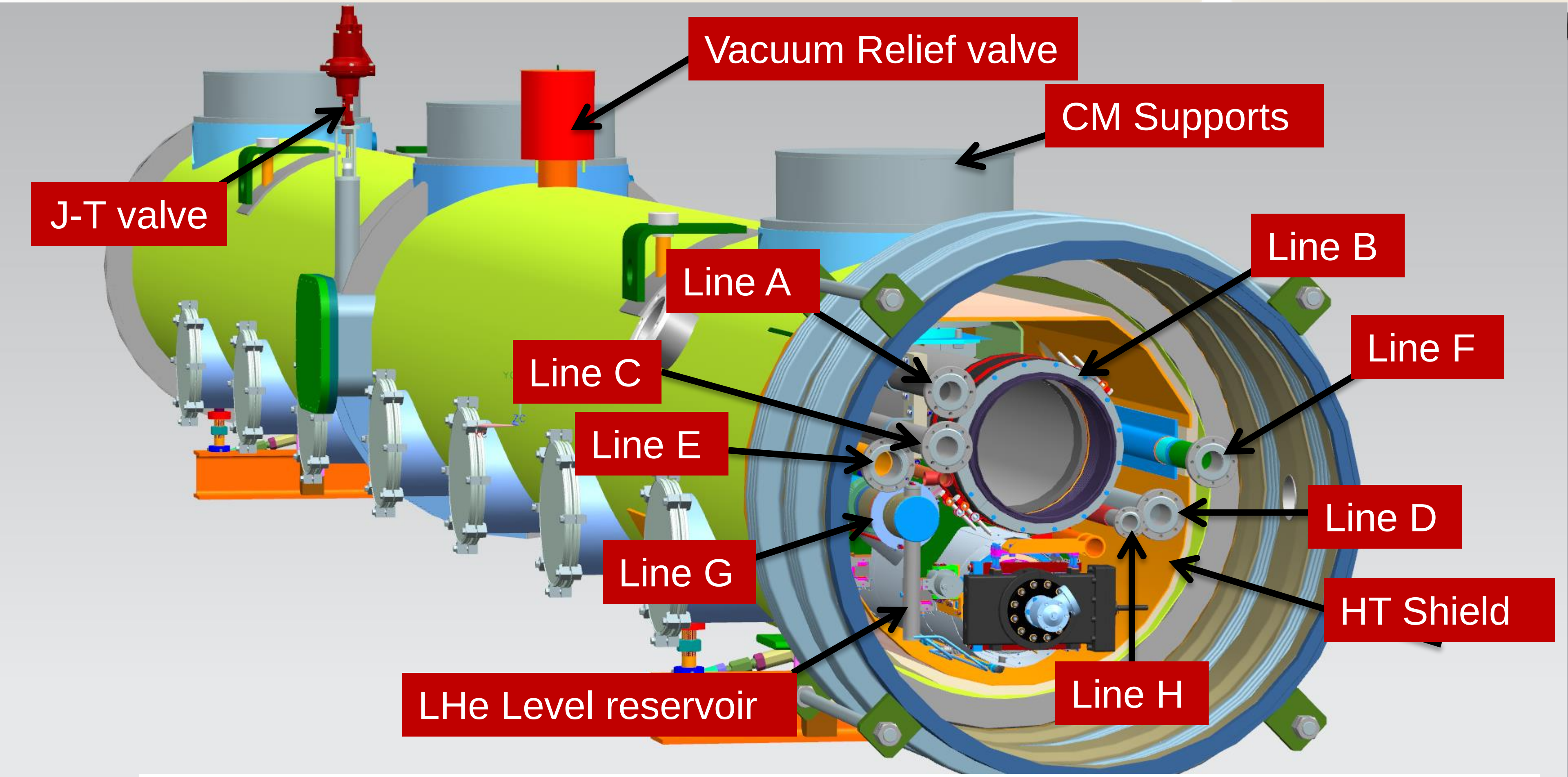
Re-purposing the SLAC Tunnel

SLAC Linac Tunnel: 11 wide x 10 feet high

It will be a tight fit!

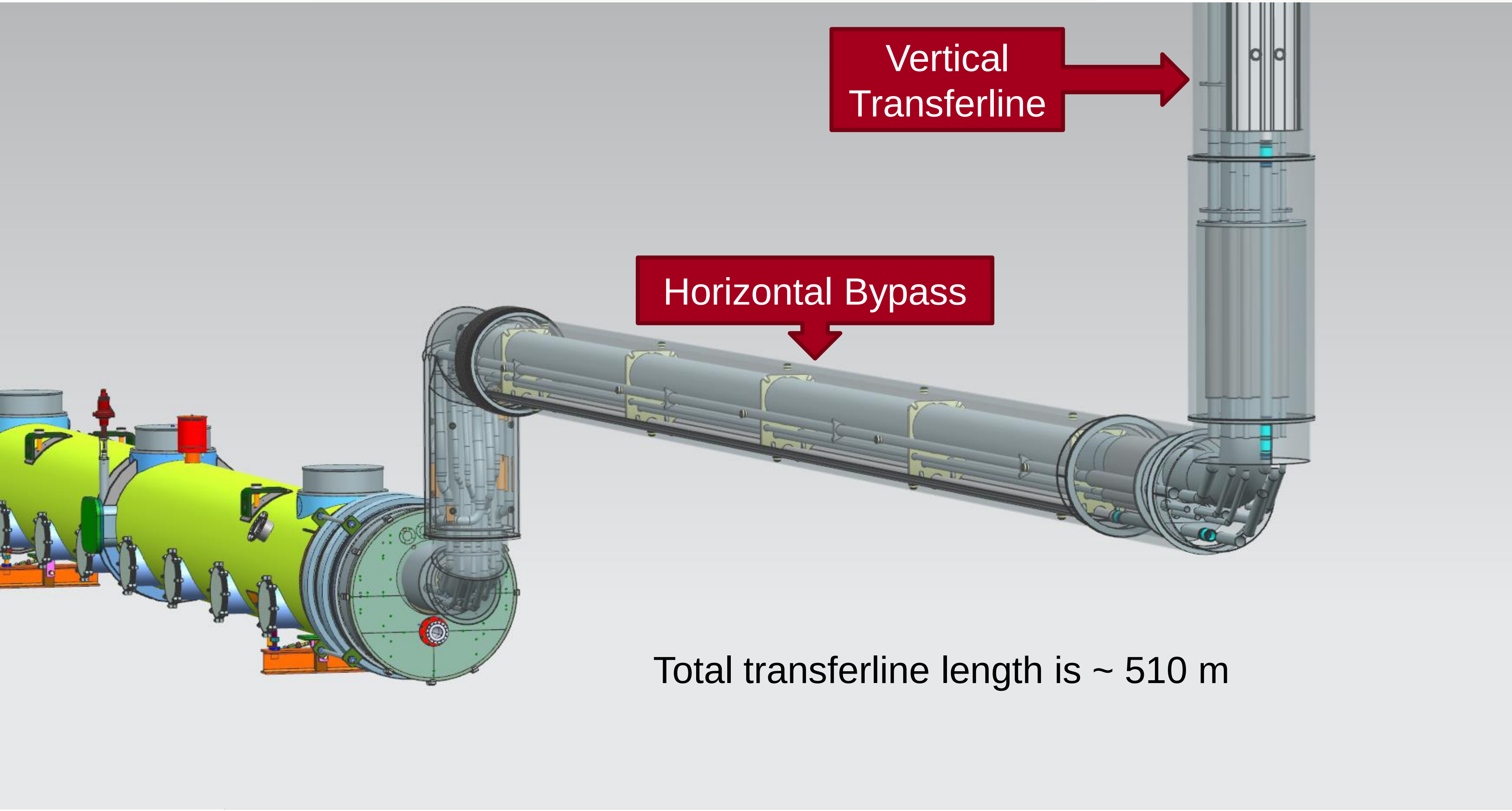


LCLS-II CM in 3-D



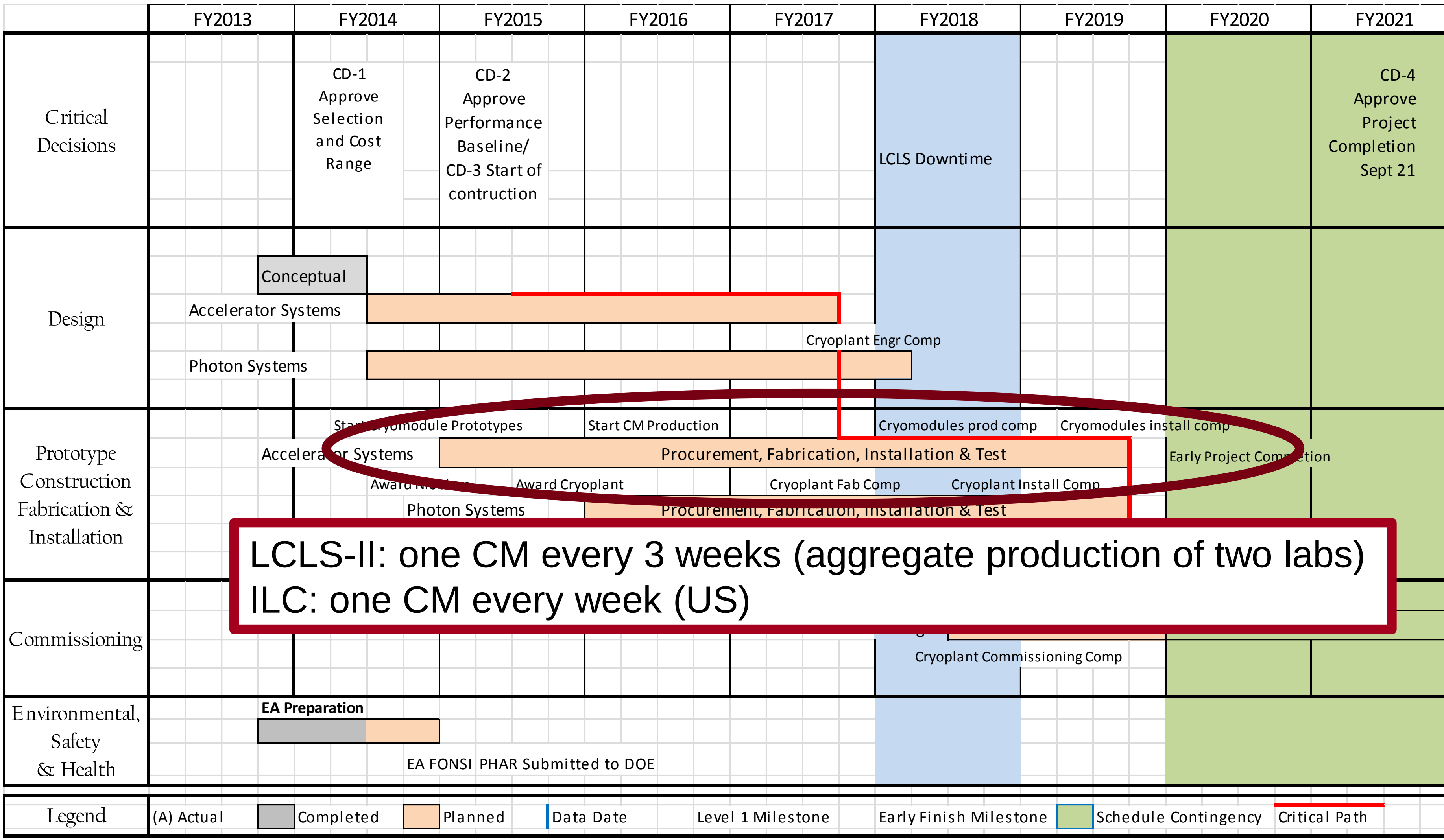
A. 2.2 K subcooled supply
B. Gas return pipe (GRP)
C. Low temperature intercept supply
D. Low temperature intercept return
E. High temperature shield supply
F. High temperature shield return
G. 2-phase pipe
H. Warm-up/cool-down line

CM, Feed Cap and Bypass and Vertical Transferline



Total transferline length is ~ 510 m

Summary Schedule



LCLS-II: one CM every 3 weeks (aggregate production of two labs)
ILC: one CM every week (US)

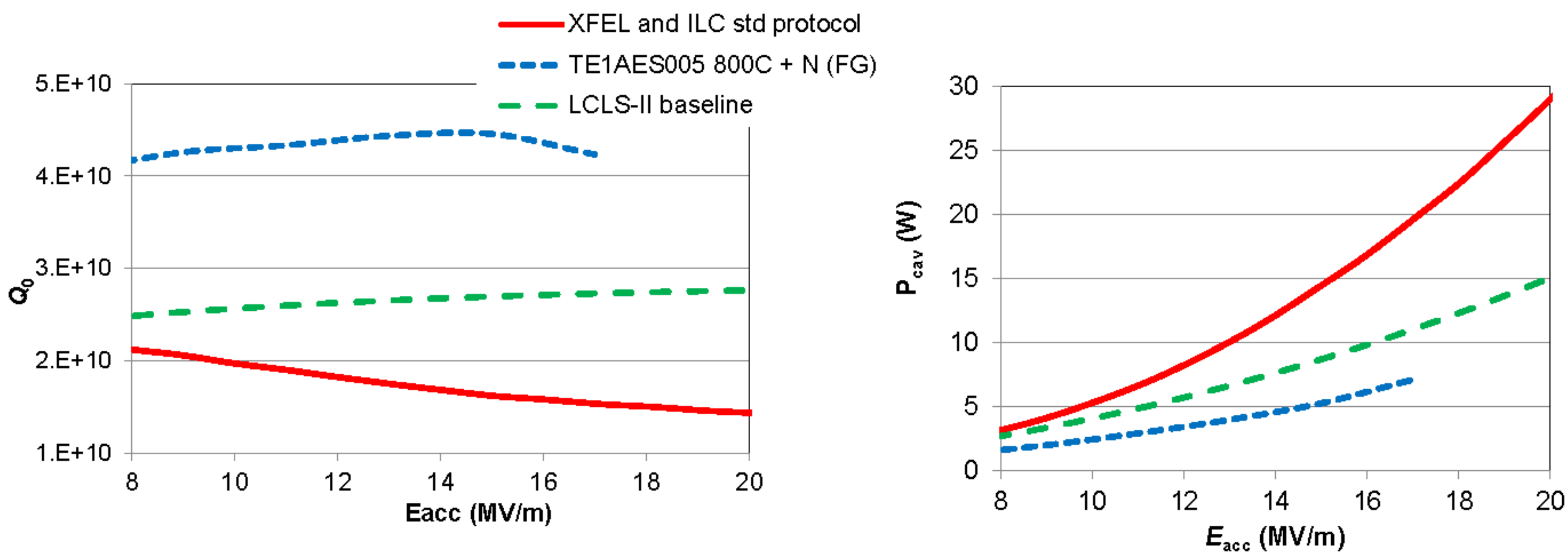
Outline

1. Industrialization of 1.3 GHz SRF technology
   - 1990's to present
   - TESLA, E-XFEL, and ILC (also CEBAF 12 GeV)
2. LCLS-II
   - Free Electron Laser at SLAC – based on ILC / E-XFEL SRF
3. SRF for LCLS-II
   - Low cryogenic-loss cavities: 'N_2 doping' process developed by Fermilab
   - Multi-lab partnership
4. Implications for ILC

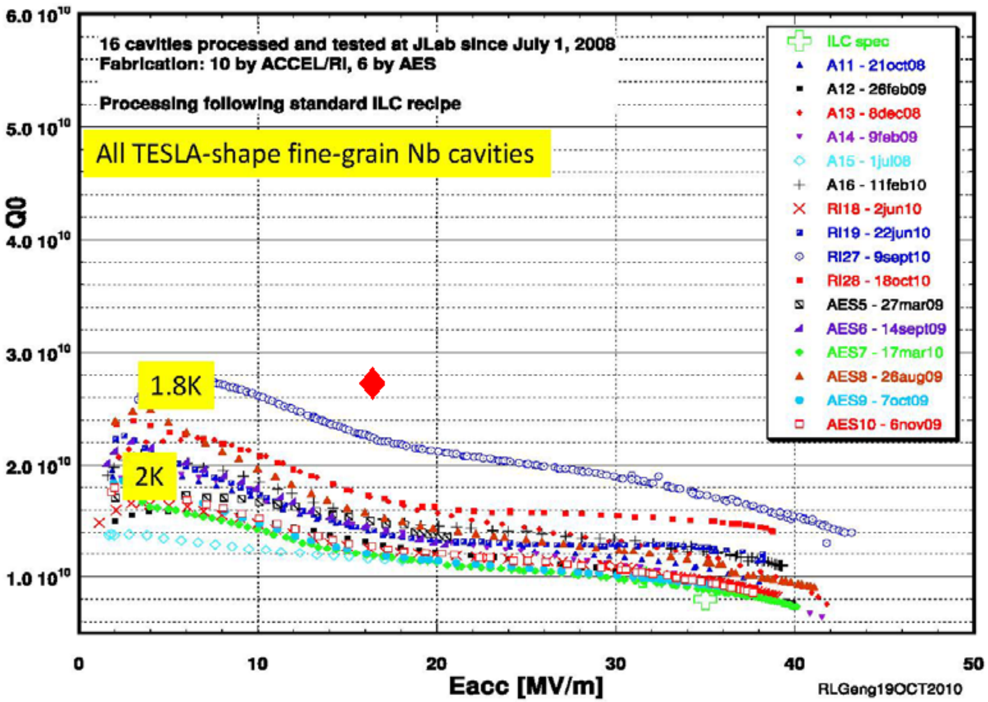
Motivation for High Q_0 R&D

High Q0 doping developed by Fermilab

- High Q_0 is a surrogate for low rf losses = low dynamic cryo heat load
- New Nb surface doping phenomenon with significantly lowered $R_{s\text{-BCS}}$ and $R_{s\text{-residual}}$ discovered 2012-2013
- Our mission: expedite development for use in LCLS-II



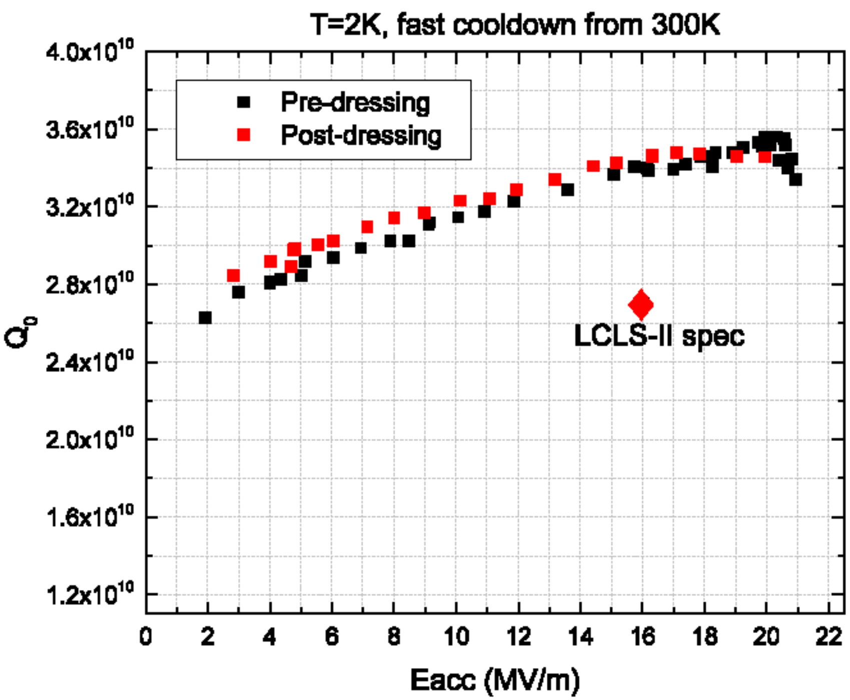
Motivation for High Q_0 R&D



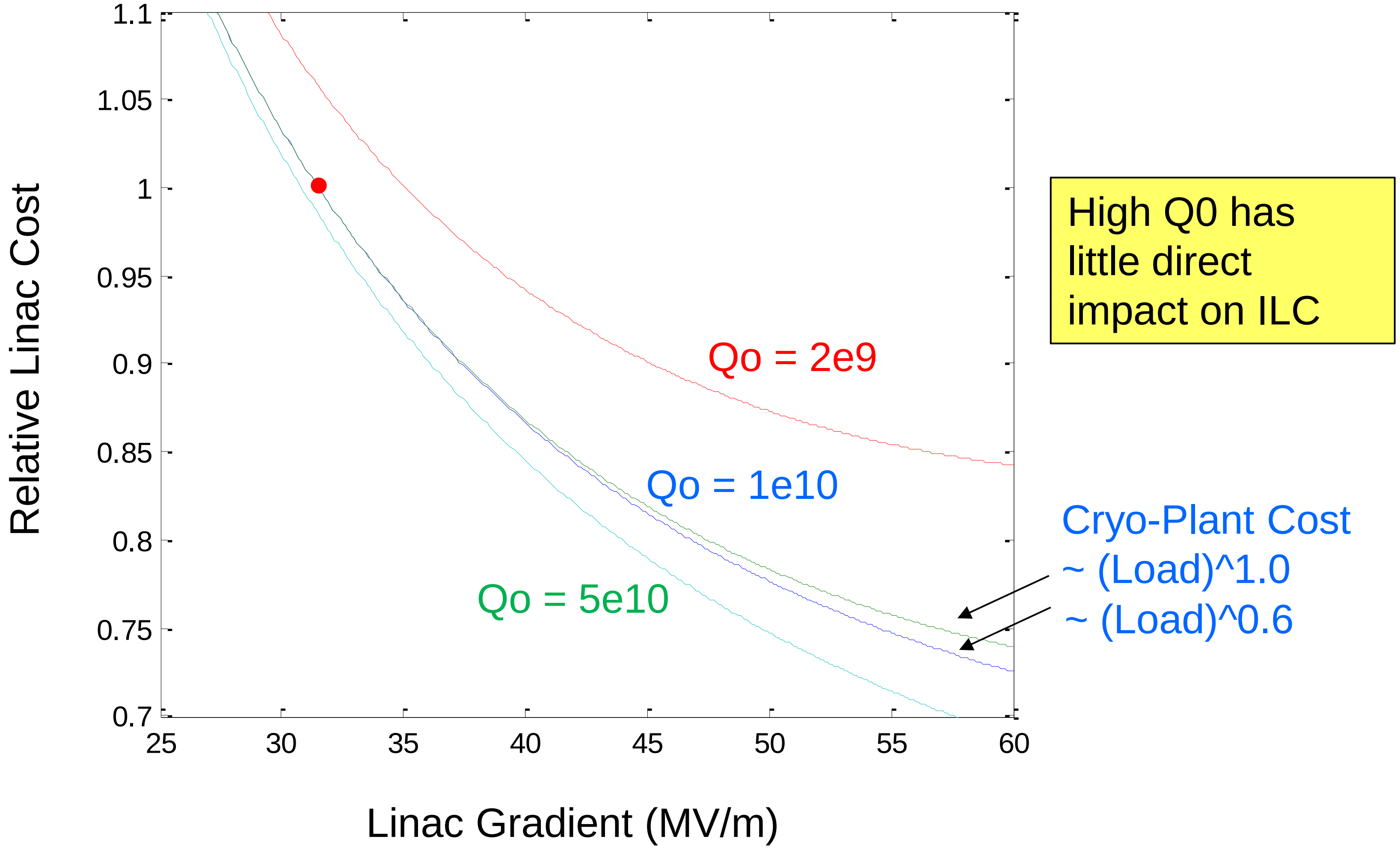
"The best cavities of 2010"

The SRF world is changing

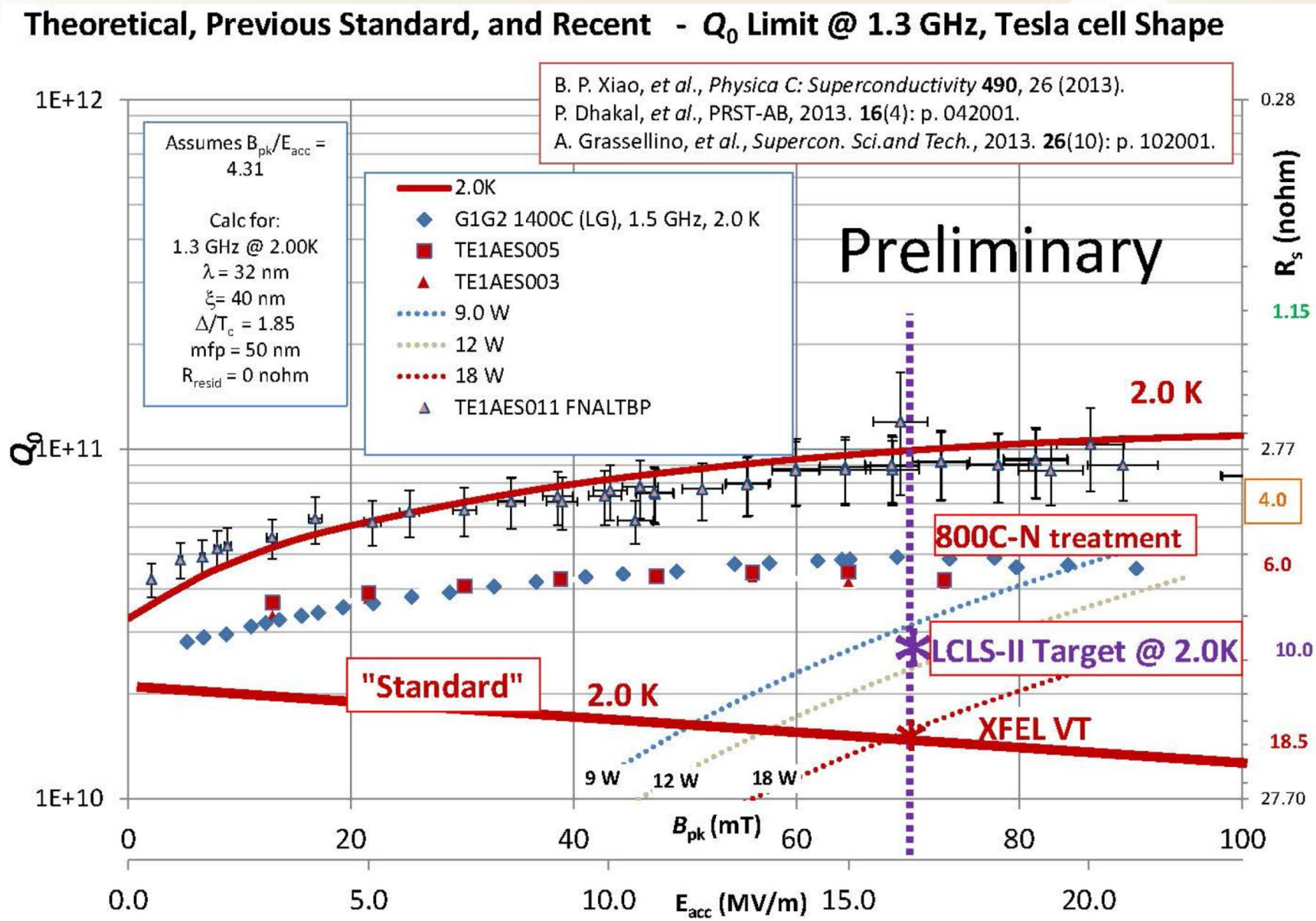
"The best dressed cavity of 2014"
(so far)
TB9AES011



Americas ILC Linac Cost Versus Cavity Gradient and Qo

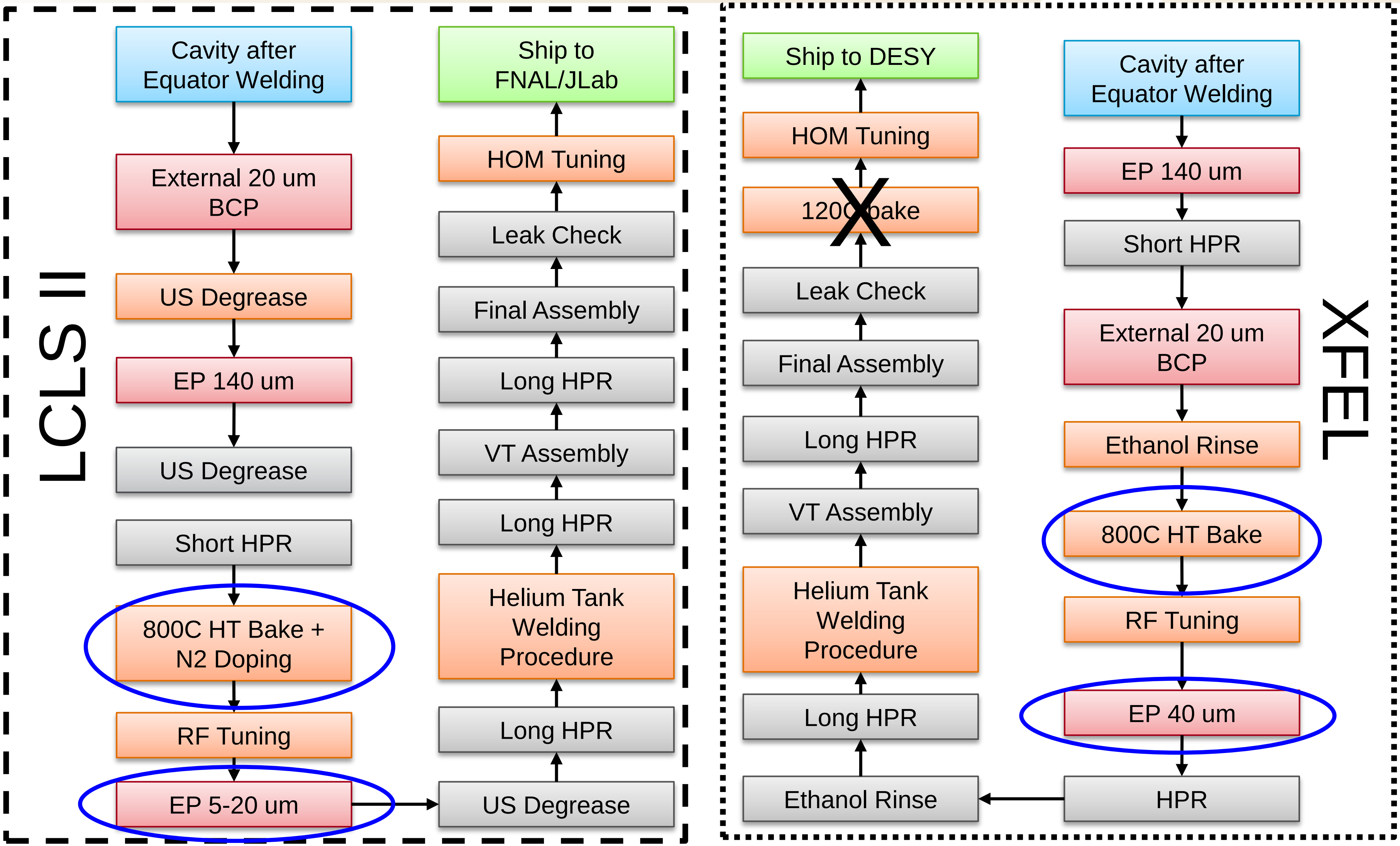


Q_0 picture still looks good for LCLS-II, but new discipline will be required



FNAL IB4 Vacuum Oven

LCLS II vs. XFEL Industrial Cavity Processing Recipe comparison: Change 2 steps



High Q0 Program – a collaborative effort
(Feb 2014 Plan)

- ~30 single-cell tests at Cornell, FNAL, and JLAB
  - **By July 2014** ***(25 Tests Completed)***
- 19 nine-cell prep / test at Cornell, FNAL, and JLAB
  - (All cavities to be supplied by FNAL)
  - **By October 2014 →**
- Performance verification in horizontal tests of 6 fully dressed cavities (3 Cornell / 3 Fermilab)
  - to understand Q_0 preservation
  - evaluate the effect of Helium vessel dressing on Q_0,
  - obtain Q_0 data under cryomodule-like conditions,
  - study residual magnetic fields for the shielding optimization,
  - develop optimized cool-down/thermal cycling procedures.
  - **By November 2014**

Fermilab – 9 cell Vertical tests (Aug 2014)

	First pass	Second	Q (2K, 16MV/m)	Quench [MV/m]
TB9AES011	OK	OK	**3.4e10**	**21.5**
TB9ACC015	OK	OK	**3.5e10**	**24**
TB9ACC012	Quench (small removal for R&D)	~Ok	**3.4e10**	**15.6**
TB9AES026	OK		**2.75e10**	**21.5**
TB9AES003	OK	OK	**2.5e10**	**27**
TB9AES027	OK		**4e10**	**-- (FE admin limit at 18)**
TB9AES028	Q-switch/quench @ 14.5 (defect)	OK	**4e10**	**25.5**
TB9AES020	Quench @ 14 (defect)	~ Ok	**4.1e10**	**15.5**
TB9AES024	September 2014			
TB9AES021				

JLab 9-cell Vertical Tests (August 2014)

Cavity name	Q @ 2K, 16 MV/m	quench field (MV/m)	radiation onset
AES031	3.4E+10	17.4	none
AES032	2.6E+10	18.2	13 MV/m
AES033	3.4E+10	16.4	none
AES034	September 2014		
AES035			
AES036			

Cornell 9-cell VT status

N-Doped 9-cell	1st Pass *	2nd Pass **	Qo at 16MV/m, 2K	Quench	Status
AES018	Done	Done	3.2E10	21MV/m	
AES022	Done	On going (VT Sept 11th)	2.0E10	24MV/m	FE limit, will be processed again
AES023	On going (VT Aug. 21st)		3.4E10	14 MV/m	Ready for VT
AES029	On going (VT Aug. 28th)				Bulk VEP, N2-dope tuning, done
AES030	On going (VT Sept 4th)				Bulk VEP, N2-dope done

LCLS-II High Q0 R&D Program – Preliminary Results

High Q0 testing done at 3 labs: Fermilab (from 2012); JLab and Cornell (2014)

High Q0 Program 9 cell results		
	Q0	E_acc (MV/m)
Average	3.26E+10	20.0
Number of cavities tested; some multi-pass		
14		

Only one vertical test Q0 below 2.3E10

Initial results meet LCLS-II VTS High Q0 criteria

Q0 preservation

Field emission

- Contaminant-free assembly process

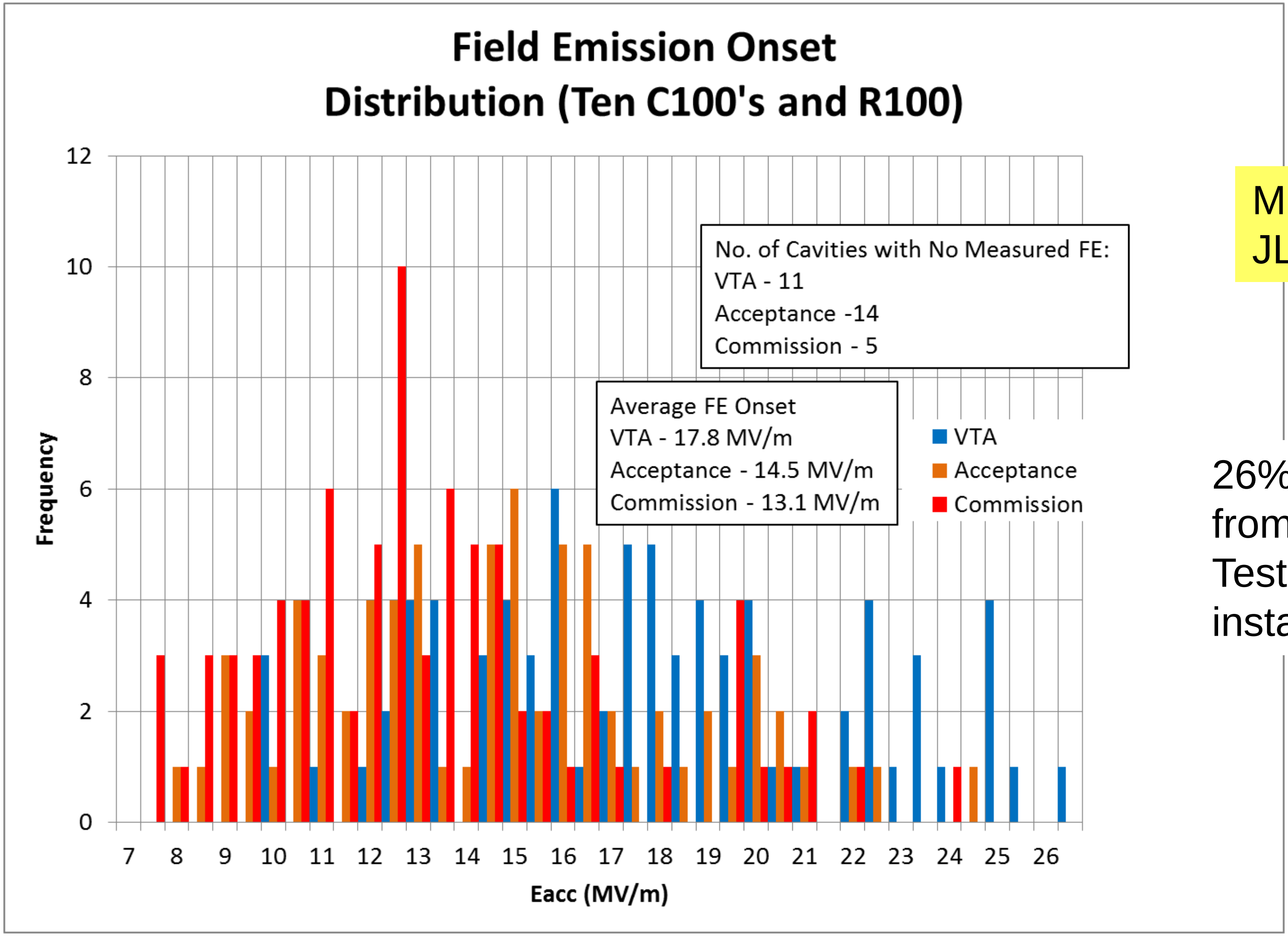
Magnetic shielding to keep < 5 mGauss

- Possible new features such as active external coils

Cool-down rate

- High rate of cool-down may be necessary
- As much as 2 – 3 Kelvin/minute through 9.2 K transition temperature
- Key may be high delta-T within Nb to “sweep out” magnetic flux
- We have some concepts for fast cooling
- Uniform cooling of bimetallic joints (? Requirement TBD)

Field Emission Onset



Mike Drury, JLab

26% reduction from Vertical Test to CM installation

Effect of cool-down *speed-through-transition*

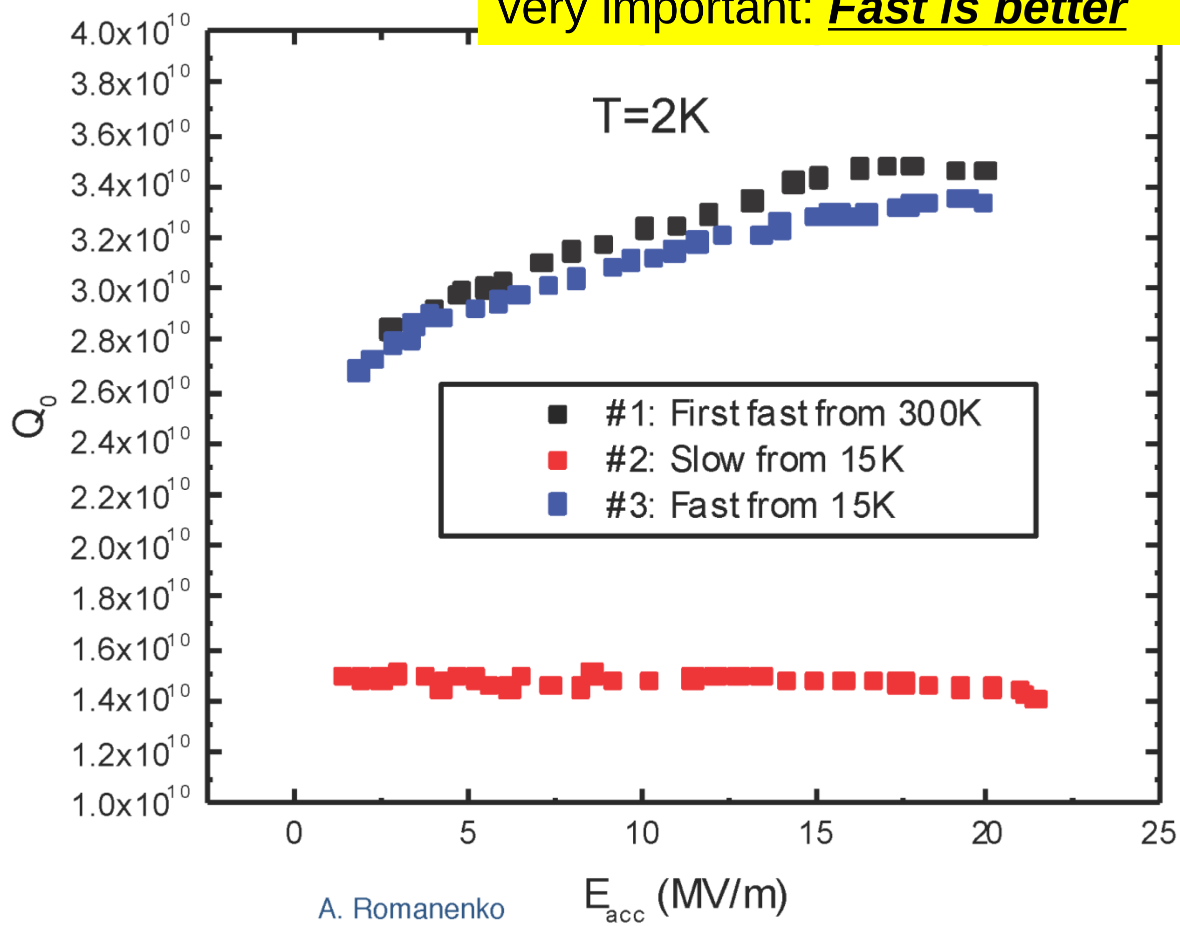
Cool-down speed appears to be very important: ***Fast is better***

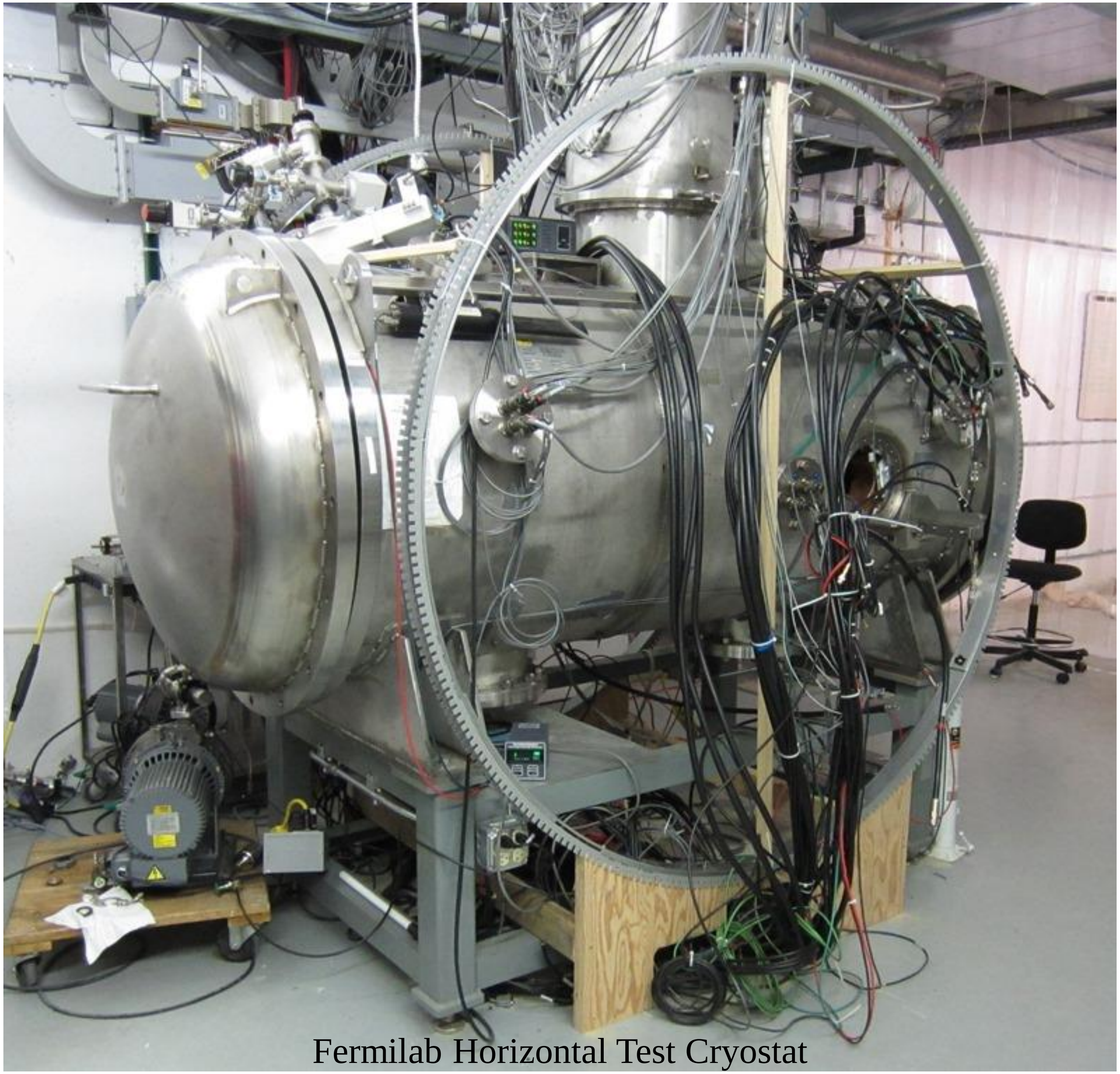
"Dressed" cavity results under different cooling regimes.

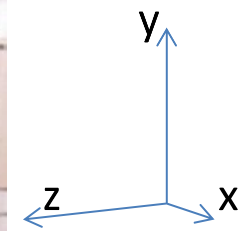
- Thermogradient-generated fields have no impact on Q in VT, slow cooling through T_c has dramatic effect.

  [fast ~1.8K/min; slow ~0.3K/min through 9.2K]

- Precautions will have to be taken in CM to obtain fast cooling through transition.

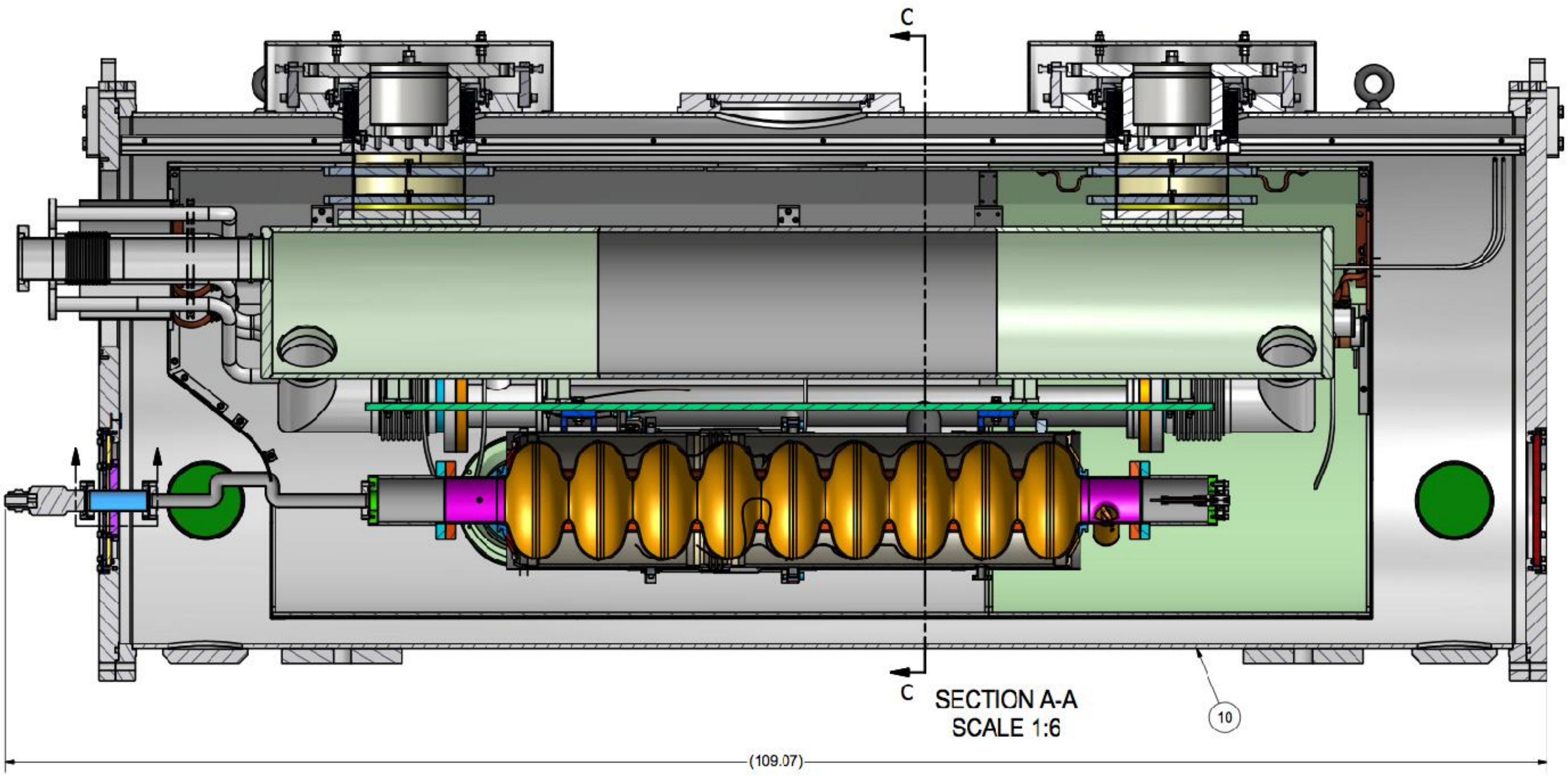






Fermilab Horizontal Test Cryostat
With Three Axis Magnetic Cancellation

LCLSII Cavity Tests in the Cornell one-cavity Horizontal-Test-Cryomodule (HTC)



- Small modifications were needed to host a 9-cell cavity (changes to 2-phase line, cavity support).

Hasan’s suggestion:
“Double the frequency & apply high Q”

Triple? → LCLS-II requires 16 3.9GHz ‘harmonic linearizer’ cavities. →
Try high Q

State of the art with ILC/XFEL protocol: (From H. Edwards / E. Harms:)

3.9 GHz cavity Q's at 15MV/m, 2K				
	date	Qo@15MV	HOM	process, comments
9cell	20080201	2.8	n	bcp, Flash
	20080722	1.8	y	
	20080827	2.5	n	
	20080207	2.2	n	bcp, Flash
	20081027	2.1	y	
	20110607	2.8	y	bcp
	20110630	2.8	y	bcp, baked on stand, from Rs should be 1.28 higher than just bcp
	20140422	3.8	n	bcp, baked at MP9 , repaired cavity

Outline

1. Industrialization of 1.3 GHz SRF technology
   - 1990's to present
   - TESLA, E-XFEL, and ILC (also CEBAF 12 GeV)
2. LCLS-II
   - Free Electron Laser at SLAC – based on ILC / E-XFEL SRF
3. SRF for LCLS-II
   - Low cryogenic-loss cavities: 'N_2 doping' process developed by Fermilab
   - Multi-lab partnership
4. Implications for ILC

Project Collaboration: SLAC couldn't do this without…

Fermilab

- 50% of cryomodules: 1.3 GHz
- Cryomodules: 3.9 GHz
- Cryomodule engineering/design
- Helium distribution
- Processing for high Q (FNAL-invented gas doping)

Jefferson Lab — EXPLORING THE NATURE OF MATTER

- 50% of cryomodules: 1.3 GHz
- Cryoplant selection/design
- Processing for high Q

Berkeley Lab

- Undulators
- e^- gun & associated injector systems

Argonne National Laboratory

- Undulator Vacuum Chamber
- Also supports FNAL w/ SCRF cleaning facility
- Undulator R&D: vertical polarization

Cornell University — Founded A.D. 1865

- R&D planning, prototype support
- processing for high-Q (high Q gas doping)
- e^- gun option

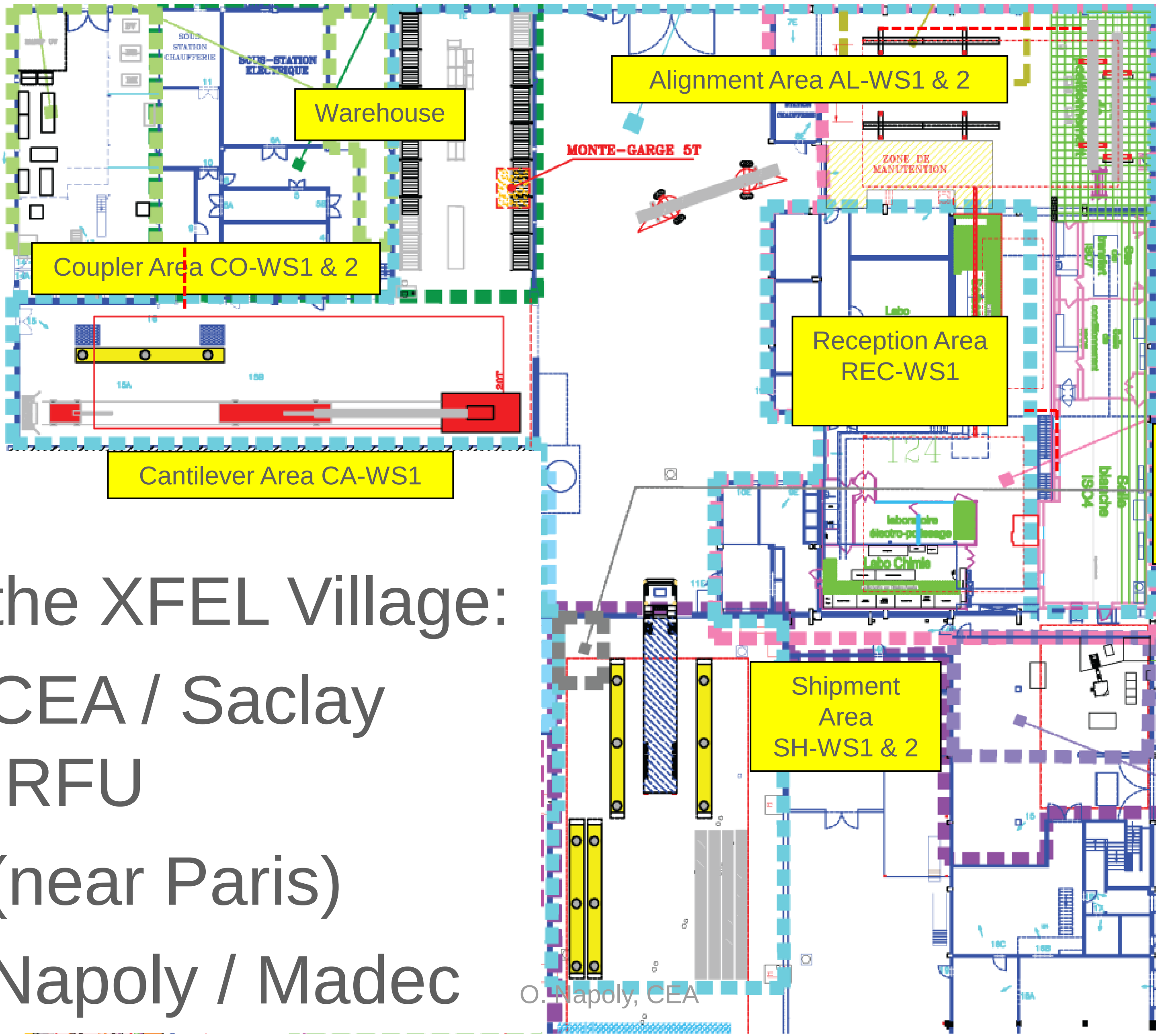
Cryomodule Production

- Follow as closely as possible XFEL industrialized path
  - Saclay (CEA) now assembling one cryomodule every two weeks
  - ***Both Fermilab and Jlab will have Saclay – style production line***
  - Guidance for touch-labor (cost) estimate

- Production-line development between three labs (and DESY)
  - (work-station development, tooling, touch-labor analysis collaborative effort)

- Desy and Saclay are special partners to LCLS-II

Assembly Hall : Workstations



the XFEL Village:

CEA / Saclay

IRFU

(near Paris)

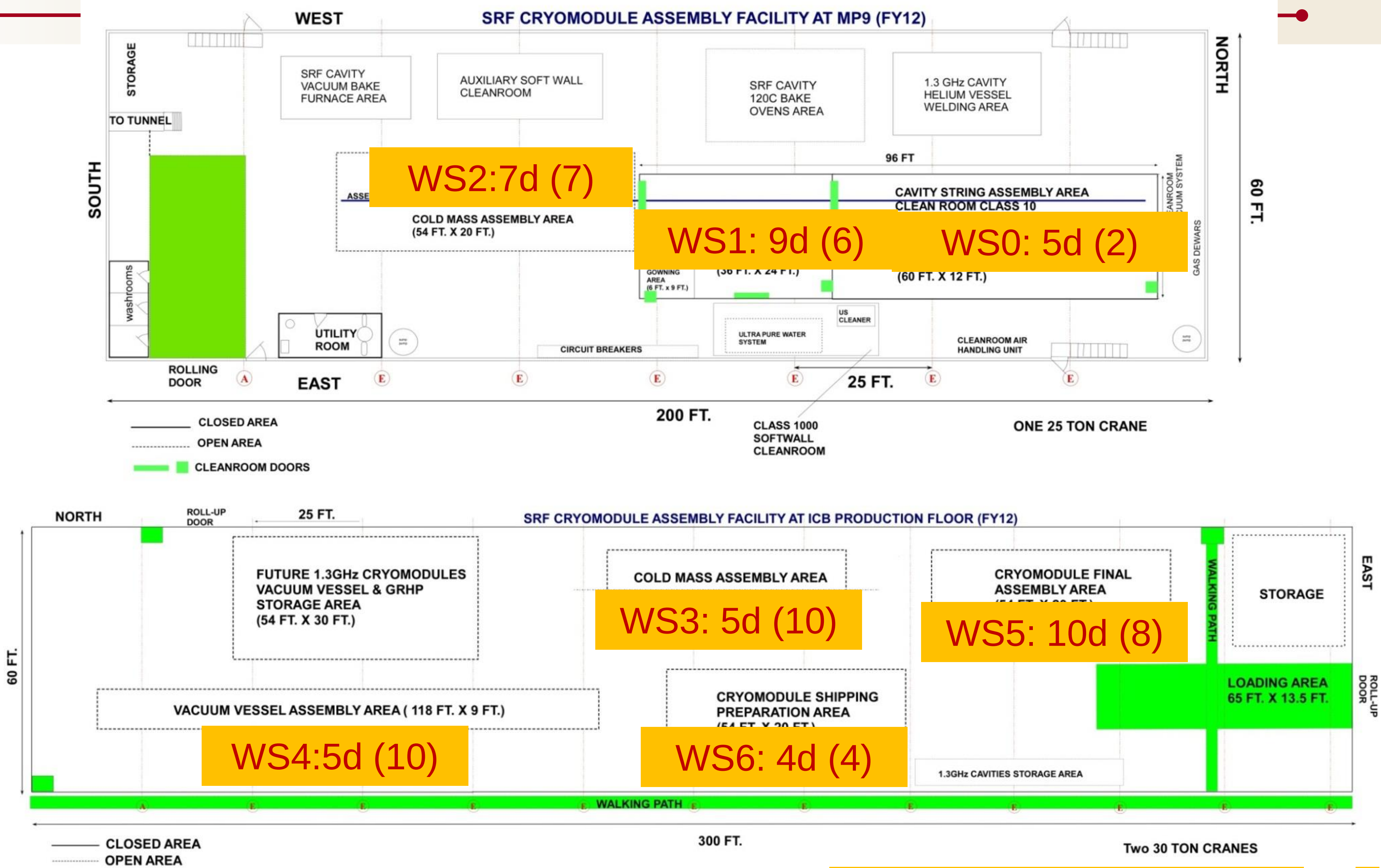
Napoly / Madec

Fermilab SRF

25 years experience with ILC / TESLA design

- FNAL has been building SRF Program since 2006
  - Extensive infrastructure – can be used for LCLS II
    - Inspection, EP, tumbling, HPR, VTS, HTS, assembly, CMTS…
    - Ongoing SRF Program supports facility maintenance
  - Cavity & cryomodule design and fabrication (low β and 1.3 GHz)
  - Originally focused on ILC (XFEL CM design, starting point for LCLS II)
    - Now focused on CW applications (PIP II) => complements LCLS II
  - Material & Cavity Processing R&D – now pursuing High Q_0 R&D
- Built three cryomodules of "LCLS II type" (pulsed operation)
  - CM1 successfully tested
  - CM2 currently being tested (most cavities reached 31.5 MV/m)
  - 3.9 GHz (successfully being operated in FLASH)
  - PIP II designs build off this experience

Capabilities and Infrastructure (existing): FNAL 1.3 GHz CM Assembly



Total = 45 days

Workstation: duration (#peo)

Jlab SRF Overview, previous projects

~1990, Jefferson Lab (Jlab) SRF Division was created to build the CEBAF accelerator

- **43 cw cryomodules** housing 346 1500 MHz cavities
- 42 standard 8 cavity cryomodules and 1 unique 2 cavity injector cryomodule
- Peak production rate of **2 cryomodules per month**
- Cryomodules/cavities exceeded specifications (~ factor of 2 in gradient and Q_0)

~1995, Jlab FEL

- **4 cw high current** cryomodules, (3 ea 8 cavity and 1 ea 2 cavity)
- Based on the CEBAF design
- New HOM Damping and thermal management
- Higher power RF power couplers, 8 and 50 kW (final 100 kW)

25 years experience
81 Cryomodules

~2000, Spallation Neutron Source (ORNL)

- **24 ea** 3 or 4 cavity cryomodules, 23 production and 1 prototype cryomodule
- Pulsed high power proton machine
- 2 blank sheet cavity and cryomodule designs, medium and high beta
- 18 months from start to first prototype cryomodule tested

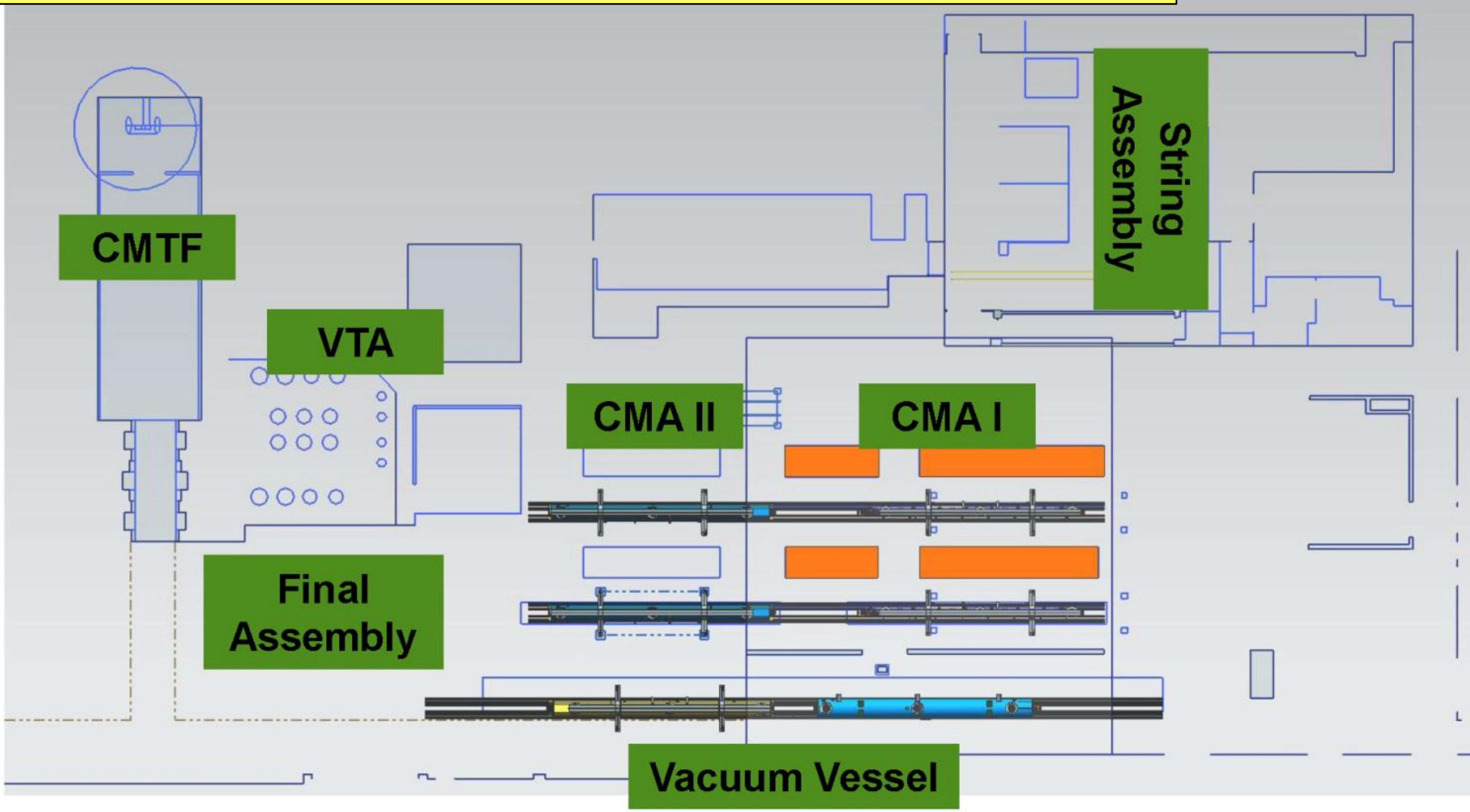
~2010, Jlab 12 GeV energy upgrade, C100 cryomodule

- Blank sheet design
- 1500 MHz, 7 cell, Low Loss type (operating at ~20 MV/m) cavities
- Same footprint of old cryomodules resulting in a 40% increase in active length fraction
- **10 ea cryomodules built (80 cavities)**, tested and installed in CEBAF → similarities w E-XFEL

JLab CM Assembly Area Work Flow

Uniquely Compact: everything in one building

Infrastructure and tooling to be adapted to XFEL/Fermilab scheme



ILC Type 3+ CM Modifications for LCLS-II (components)

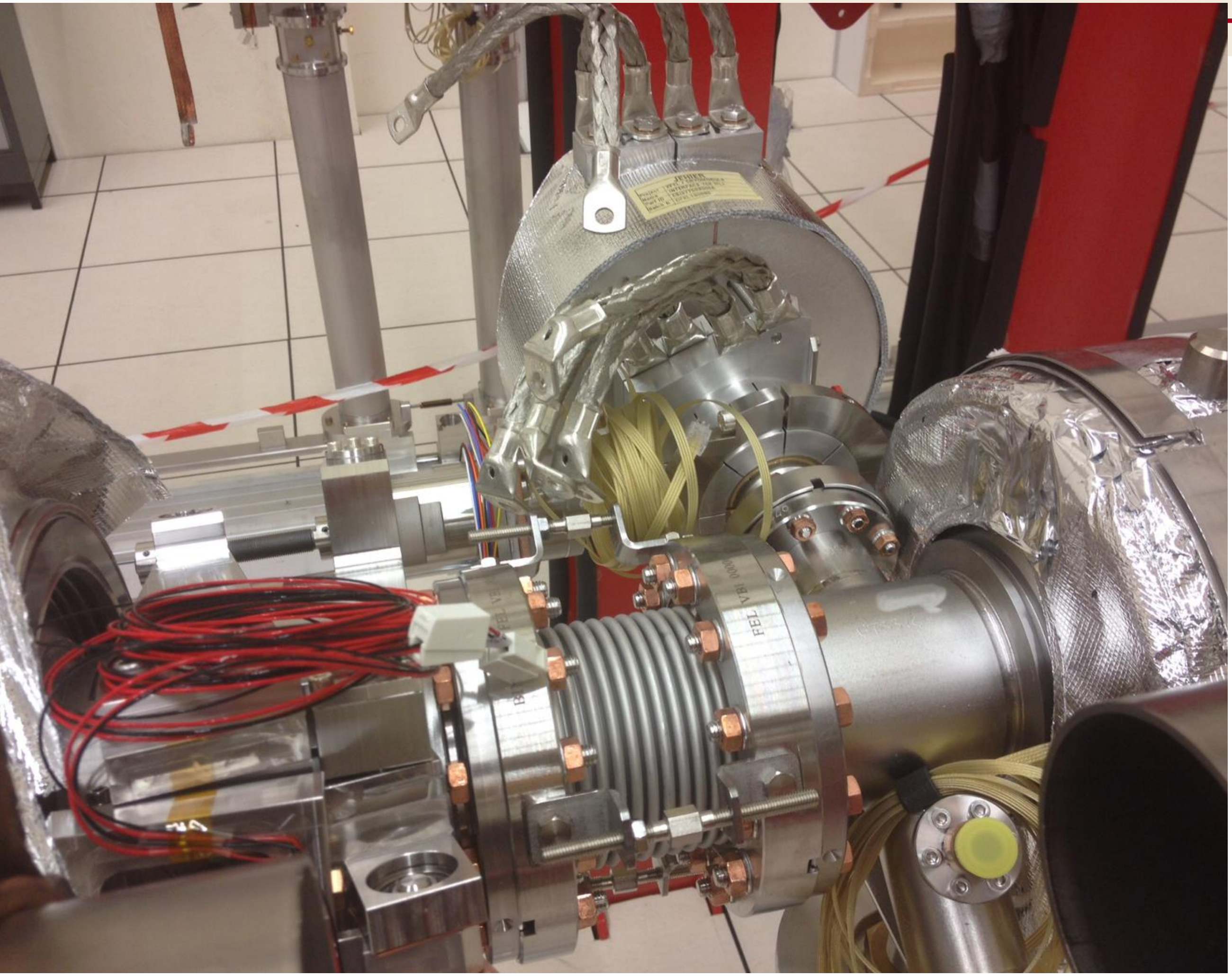
Component design – leverage existing designs optimally

- Cavities – XFEL identical
- Helium vessel – XFEL-like
- HOM coupler – XFEL-like or –identical
- Magnetic shielding – increased from XFEL/ILC to maintain high Q0
- ***Tuner – XFEL or XFEL-like end-lever style***
- ***Magnet – Fermilab/KEK design split quadrupole***
- BPM – DESY button-style with modified feedthrough
- Coupler – XFEL-like (TTF3) modified for higher QL and 7 kW CW

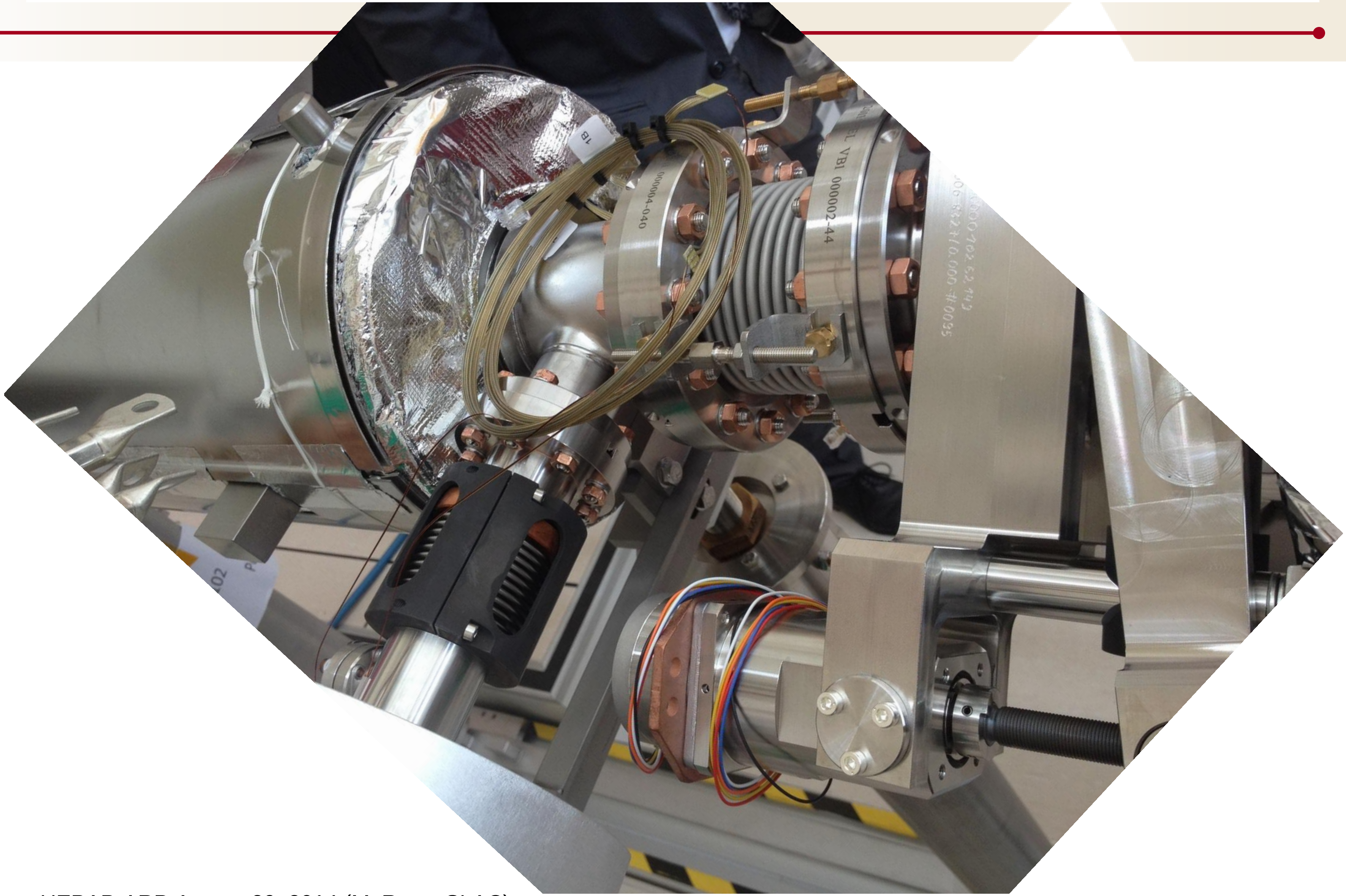
Concerns based on global experience

- ***Tuner motor and piezo lifetime: Consider access ports***
- Maintain high Q0 by minimizing flux trapping: possible constraints on cooldown rate through transition temperature

inter-cavity connection showing tuner, bellows and coupler – EXFEL Cryomodule

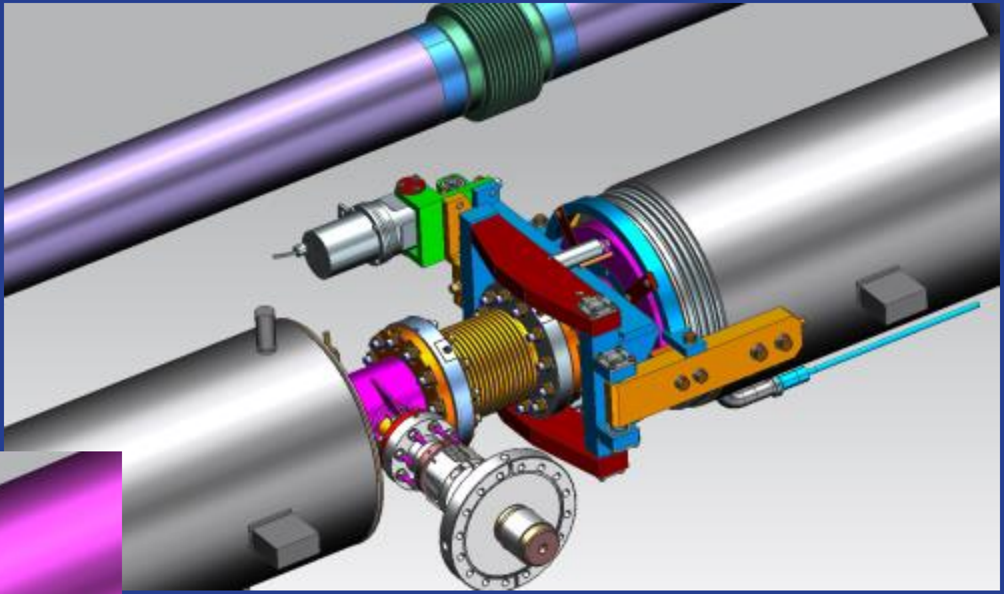


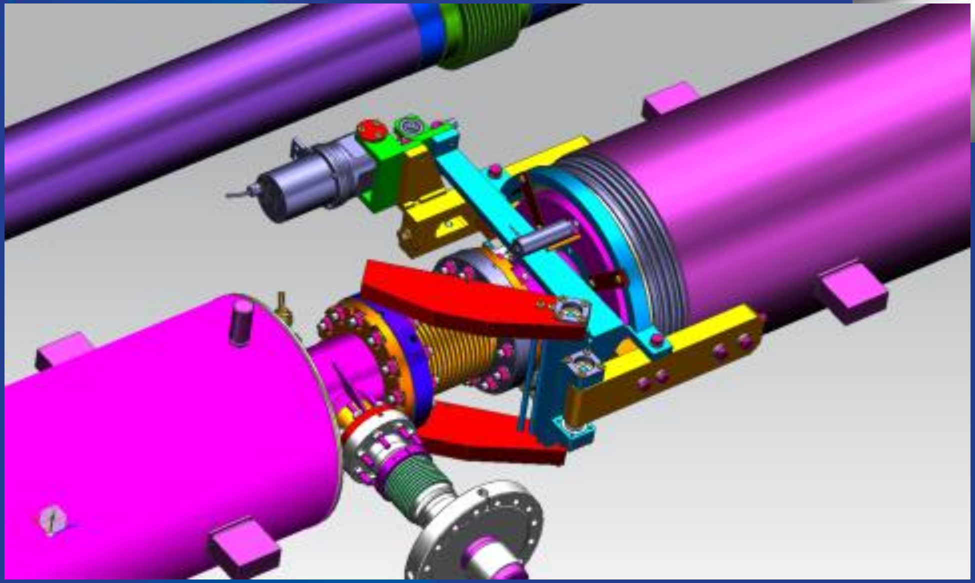
E-XFEL cavity string assembly showing inter-cavity connection



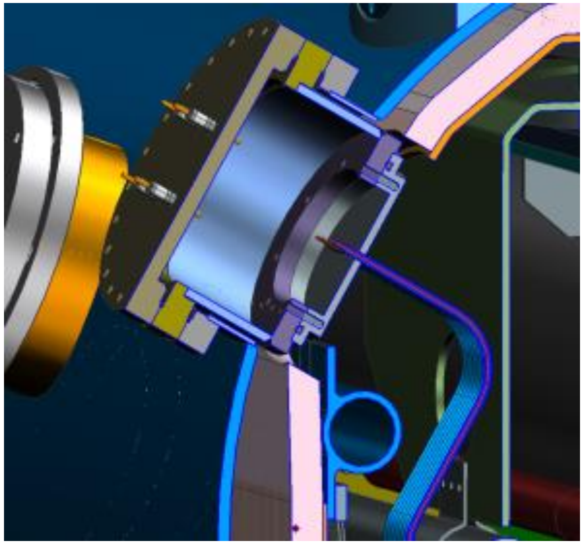
Cavity string for LCLS-II showing modified lever-type tuner

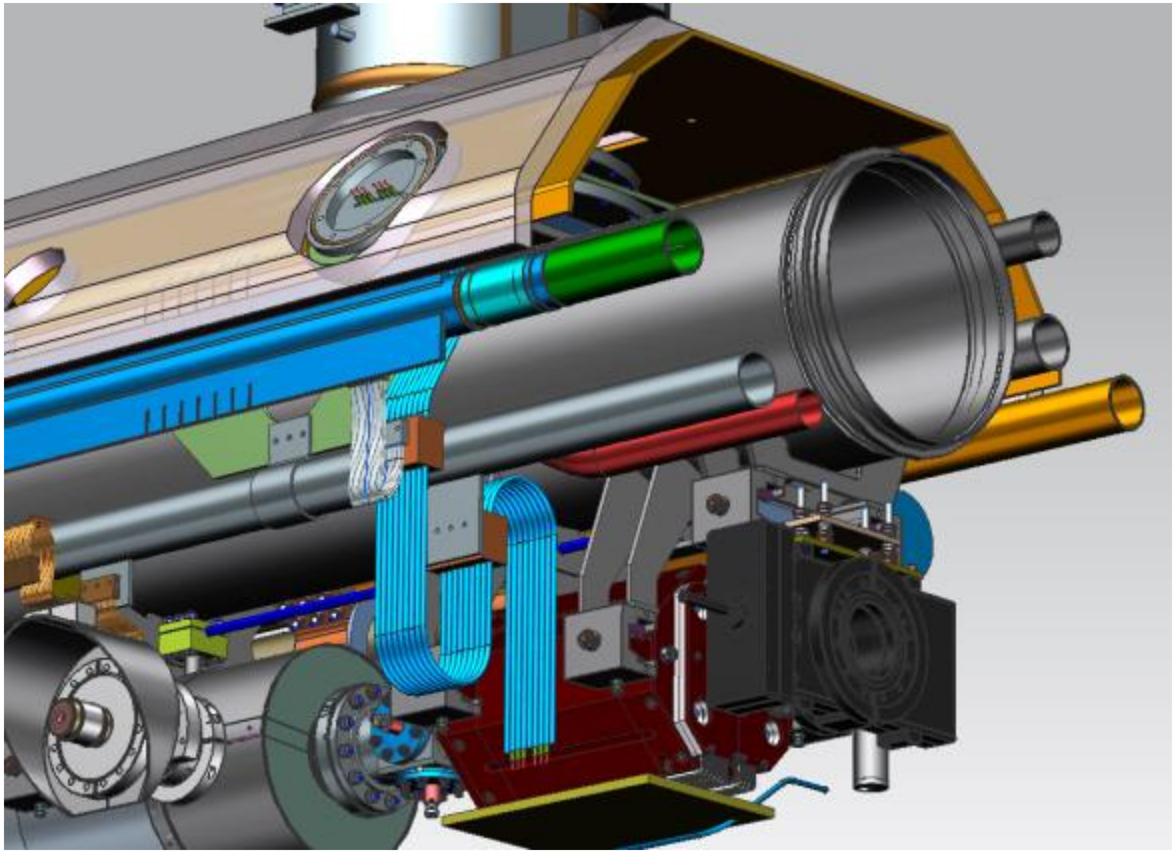
Note tuner is on opposite side: tuner access vacuum tank port may be possible





1.3GHz CM. Current Leads & Splittable Quad Magnet





Conduction cooled

intercept to 2-phase He pipe for Quadrupole

Outline

1. Industrialization of 1.3 GHz SRF technology
   - 1990's to present
   - TESLA, E-XFEL, and ILC (also CEBAF 12 GeV)
2. LCLS-II
   - Free Electron Laser at SLAC – based on ILC / E-XFEL SRF
3. SRF for LCLS-II
   - Low cryogenic-loss cavities: 'N_2 doping' process developed by Fermilab
   - Multi-lab partnership
4. Implications for ILC

For ILC: Summary

Cavity / Cryomodule:

- Cost Validation : ***few percent scale***
- Cost Reduction
  - Applied production v/v continued R&D
  - (tooling, infrastructure, and experience)
  - From C100 to EXFEL: ***factor 2 cavity cost reduction***
  - (Hasan's target)
- Technical Risk Mitigation
  - ***Demonstrate construction and performance*** of ILC-type cryomodules for science in the US

For US, the work on ILC and now on LCLS II has brought together SRF programs in a way that maximizes collaboration, efficient sharing of IP, and facilities giving the most "bang for the buck".